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WADC TECHNICAL REPORT 54-594

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Fred Newell and Graham Campbell
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Aeronautical Research Laboratory
Contract AF 33(038)-20659
Task No. 70501
Project No. 1364

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report was prepared for the U. S. Air Force by Cornell Aeronautical Laboratory, Inc., Buffalo, New York in partial fulfillment of Contract AF33 (038)-20659, under Task 70501, "Artificial Stability and Control," a part of Project No. 1364, "Flight Control Technical Requirements".

The program was performed by the Flight Research Department of Cornell Aeronautical Laboratory, Inc., under the sponsorship of the Aeronautical Research Laboratory, Wright Air Development Center, Air Research and Development Command, U. S. Air Force, as part of a basic program to determine optimum and acceptable longitudinal stability and control characteristics. Mr. P. P. Cerussi, staff scientist, was coordinator for the Aeronautical Research Laboratory.

ABSTRACT

A B-26B airplane elevator control system was modified and small auxiliary pitching surfaces installed so that wide ranges of stability and control characteristics could be simulated. The equipment is described briefly.

Qualitative ratings by one pilot were obtained for a range of short period frequencies and damping ratios. These evaluations were done in simulated gunnery runs and by performing fairly rapid maneuvers. Areas of varying degrees of pilot preference are obtained.

A range of phugoid damping ratios were evaluated under simulated blind flying conditions by one pilot. A consistent correlation is obtained between phugoid damping and pilot ratings, (the pilot preferring increased damping) and between phugoid damping and measured altitude variations. However, insufficient data was obtained to permit recommendation of quantitative boundaries of the pilot's preference.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Aldro Lingard

ALDRO LINGARD,
Colonel, USAF
Chief, Aeronautical Research Laboratory
Directorate of Research

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LIST OF SYMBOLS

c	wing MAC
C_m	$\dfrac{M}{\rho/2\, U^2 S c}$
$C_{m_q} = \dfrac{2U}{c} \dfrac{\partial C_m}{\partial \dot{\theta}}$	pitching moment coefficient per unit angle of pitch rate
C_{m_α}	pitching moment coefficient per unit angle of attack
$C_{m_{\dot{\alpha}}}$	pitching moment coefficient per unit angle of attack rate
C_{m_u}	pitching moment coefficient per unit airspeed
$C_{m_{\dot{u}}}$	pitching moment coefficient per unit airspeed rate
f	undamped natural frequency, cps
F_s	pilot stick force
g	acceleration due to gravity
h_i	pressure altitude
M	pitching moment ft-lb.
m	mass of airplane
n_z, g	normal acceleration, g units
$q = \rho/2\, U^2$	dynamic pressure, lb/ft ^{2}
S	wing area
T	period of oscillation, sec.
U	forward velocity, fps
u	incremental forward velocity, mph or fps

List of Symbols (cont'd)

$\dot{u}$	rate of change of forward velocity, mph/sec or fps ^{2}
V_i	indicated airspeed, mph
α	angle of attack, deg.
$\dot{\alpha}$	angle of attack rate, deg/sec.
δ_{aux}	auxiliary surface displacement, deg.
δ_e	elevator displacement, deg.
δ_s	pilot control column displacement, in. or deg.
ζ	damping ratio
θ	pitch attitude angle, deg.
ρ	density of atmosphere, slugs/ft ^{3}
τ	aerodynamic time, sec = $m/\rho U S$
ω	undamped natural frequency, rad/sec $= 2\pi f$

INTRODUCTION

Cornell Aeronautical Laboratory has undertaken for the U. S. Air Force an extensive program to obtain actual flight test data on the optimum and minimum flyable longitudinal stability and control characteristics for fighter and bomber airplanes. The aviation era has passed when adequate stability and control can be obtained with fixed surfaces and unboosted controls. It is apparent that artificial stability and irreversible boost control are necessary to make modern military airplanes useful. Once committed to equipment to provide incremental stability and control feel up to some "acceptable" level, minor adjustments might well give "optimum" characteristics. If the equipment fails, the airplane must have some "minimum flyable" characteristics.

The purpose of this program at Cornell Aeronautical Laboratory is to determine in flight these "optimum" and "minimum flyable" characteristics. The work has been carried out on a B-26B light bomber and an F-94A jet fighter. Artificial longitudinal stability and control systems have been installed to provide extreme variations in the following parameters: short period mode frequency and damping, phugoid mode period and damping, and control forces and positions needed to trim and maneuver. This report describes the evaluations on the variations in short period and phugoid characteristics using the B-26. Reference 1 reports tests by twelve pilots on the B-26 with various force levels and simulating different types of feel. References 2 and 3 give the results of theoretical calculations made before installation of equipment on the B-26 and F-94 respectively. Reference 4 describes the equipment installations in both airplanes. The data from the flight tests on the F-94 will be presented in a later report. Additional flight programs on variable gear ratios and variable breakout forces will be made on both airplanes. For the short period evaluations reported here, the one pilot was given a series of configurations to evaluate qualitatively. Standard maneuvers were performed and the pilot gave his opinion on the acceptability of each configuration. The steady state F_s/g and δ_s/g were kept constant as the frequency and

damping ratio of the short period were varied. These qualitative opinions were plotted vs. frequency and damping ratio, and areas of varying degrees of acceptability were determined.

For the phugoid evaluations, a wide range of frequency and damping were also available. Under contact flight conditions the pilot observed no appreciable difference in flight characteristics even with extreme variations in both frequency and damping. Flights were also made using a blind flying hood to closely simulate instrument conditions. On these flights the pilot's opinion of the longitudinal control varied and he qualitatively rated the configurations. Also, time histories of airspeed and altitude were recorded and analyzed for 30 minute runs under instrument conditions. These time histories were reduced to power spectral densities, and correlated with phugoid damping ratio. The phugoid frequency was kept essentially constant as the damping ratio only was varied during these blind flying tests.

The following sections describe the equipment briefly, describe the short period evaluation tests and present the data, and describe the phugoid tests and present the data.

EQUIPMENT

An elevator irreversible boost and control feel system was installed at Cornell Aeronautical Laboratory in the Douglas ETB-26B serial #44-34653 (Figure 1). Emphasis was placed on versatility of the installation. This particular model of the B-26 has two sets of pilot controls. For this program, the left elevator control column was separated from the elevator. Two hydraulic struts were installed as position servos, one attached to the elevator horn in the rear of the airplane to actuate the elevator, and the other attached to the left control column to actuate it. The struts are controlled by electro-hydraulic transfer valves (Moog Valve Co. model #V-20). Linear feedback potentiometers mounted on the struts provide signals which are mixed electrically with the desired inputs to each servo to give a resulting error voltage to the valves. The inputs to the stick servo, (with adjustable gain) are (a) pilot stick force and (b) pilot stick trim. The force input with the position feedback causes the servo to act as a linear spring. The elevator servo was positioned proportional to (a) pilot stick force, (b) angle of attack, (c) angle of attack rate and (d) pilot elevator trim.

The pilot's stick force signal is obtained from strain gages mounted on the control column. By means of a switching arrangement the force signal can either go through or bypass a q-divider, making the pilot's input to the stick or elevator servos proportional to either F_s or F_s/q. A vane, mounted on a boom extending from the nose of the B-26 drives a selsyn to provide the angle of attack signal. A repeater selsyn permits this signal to be manually nulled for any desired airspeed.

The angle of attack rate signal is provided by a tachometer generator driven by a small electrical servomotor which is positioned by the angle of attack signal. The pilot trim inputs to the stick and elevator servos are potentiometers across a fixed voltage, to enable the pilot to trim out a force signal when desired.

The angle of attack and angle of attack rate signals (ΔC_{m_α} and $\Delta C_{m_{\dot{\alpha}}}$)

to the elevator are used to change the short period frequency and damping. The stick force signal to the elevator is then adjusted to keep the steady-state F_s/g constant. The stick force signal to the stick servo was kept constant, yielding a constant F_s/δ_s and since the F_s/g was kept constant, so also was δ_s/g. The co-pilot has a control panel (Figure 2) with which he can set the sensitivities of all of these inputs. By adjusting these knobs in flight, extreme ranges of the short period characteristics can be obtained without varying F_s/g and δ_s/g.

Early in the design stages of this artificial stability project, calculations of the pitching moments required to control the phugoid showed small fractions of one degree of elevator would be necessary (Reference 2). As a result of these calculations, a small auxiliary pitching surface with a maximum C_m of ±.0014 was installed (Figure 3). The purpose of this surface is to modify phugoid characteristics only and, therefore, a short response time of the surface actuator is not necessary. The derivatives used to modify the phugoid were C_{m_u} and $C_{m_{\dot{u}}}$, but it was not desirable to pass the sharp-edged gusts that might appear in the u and $\dot{u}$ signals. A surface of 3.5 ft.^{2} total area and ±15 degrees travel was installed on each side of the fuselage near the horizontal tail, driven by a Pioneer P-1 servomotor. The motor was geared down such that the maximum velocity of the surface was 2 deg/sec. This velocity is fast enough to produce a sine wave with stop-to-stop amplitude with a 47 second period. This velocity is also slow enough so that the transient g response to a 2 deg/sec linearly increased ramp input of elevator for a short time is negligible. Regardless of the shape of an airspeed gust, nothing worse than this 2 deg/sec ramp can pass the velocity limiter.

The form of the derivatives was such that the incremental damping ratio would remain constant over a trim airspeed range, and the incremental frequency would vary linearly with trim airspeed. This approximates the way the phugoid characteristics of a normal subsonic airplane behave. The form of the inputs used were $\dot{u}/q$ and $\Delta\,(1/q)$ (Reference 2). To obtain the $\dot{u}$ signal, a Kollsman Airspeed Synchrotel (airspeed indicator driving a selsyn) positions a servomotor from a modified Sperry A-12 turn control. A rate generator in the turn control is driven by the motor. The angular po-

sitions of the Synchrotel and of the motor are proportional to airspeed, and the generator output is then proportional to $\dot{u}$.

The "q-divider" consists of a small servomotor positioned by a signal proportional to q. q is sensed by a Statham strain gage pickup. Four potentiometers are ganged on the output shaft of the motor. One is used for position feedback. Each of the others is loaded such that its output is $1/q$ times its input. One potentiometer thus has a voltage proportional to $\dot{u}$ applied to it, and its output is proportional to $\dot{u}/q$ and is used as an input to the auxiliary surface to simulate $C_{m_{\dot{u}}}$. Another potentiometer has a fixed voltage E on the input, and the output is E/q. This E/q voltage is nulled at the trim airspeed in flight, and the incremental voltage is $\Delta\,(E/q)$ or $E\Delta\,(1/q)$. This is the signal source for C_{m_u}. The fourth potentiometer on the q-divider servo converts F_s to F_s/q.

Varying the phugoid characteristics in flight consists of adjusting the sensitivities of $\delta_{aux}\,/\,(\dot{u}/q)$ and $\delta_{aux}/\Delta\,(1/q)$. These are controlled by two knobs on the co-pilot's panel (Figure 2).

The co-pilot's control column is always rigidly connected to the elevator. In case of malfunction of the boost system the hydraulic pressure can be dumped, enabling the co-pilot to take over the control of the airplane.

The pilot's column is separated from the elevator while the boost system is operating. However, a spline and dog arrangement allows the pilot's column to be re-engaged to the elevator for normal flight. All take-offs and landings have been made in this normal configuration.

The auxiliary surface servo operates independently of the elevator and stick servos. Thus the phugoid characteristics can be varied both when the boost system is operating and when using standard unboosted controls. The phugoid evaluations were made primarily with the stick and elevator servos inoperative (airplane flown by means of its standard longitudinal controls). A pictorial block diagram of the control system is shown in Figure 4.

The important variables are recorded on a 12 channel oscillograph, including α, n_z, δ_s, δ_e, δ_{aux}, F_s, $\dot{\alpha}$ and $\dot{u}$. Other variables, including V_i, h_i, outside air temperature, and hydraulic pressure, are recorded on a photo-observer.

Reference 4 describes in detail the electronic and hydraulic components and the many safety features of the system.

EVALUATIONS OF VARIABLE SHORT PERIOD CHARACTERISTICS

Description of Tests

The frequency and damping of the short period were varied over large ranges by changing in flight the gains of the α and $\dot{\alpha}$ inputs to the elevator servo. The airplane was calibrated in flight by measuring the responses to elevator step inputs. Adjustments were made to the F_s inputs to keep the steady-state F_s/g and δ_s/g gradients constant as the frequency and damping were varied. These constant values were 66 lb/g and 1.83 in/g, approximately the values of the normal B-26, and also close to the pilot's optimum. One pilot's opinions were obtained on the acceptance of the airplane flight characteristics as its short period frequency and damping were varied. The pilot performed some maneuvers described below typical to a tactical mission in a B-26, and gave his qualitative comments and ratings immediately after doing the maneuvers.

Pilot opinion data are presented in Figure 5. This figure is a plot of the pilot's acceptance of the longitudinal response and handling characteristics plotted against the short period natural frequency and damping. On this diagram there are boundaries between the areas of degrees of acceptance. By no means are these boundaries to be construed as having been rigidly determined. The data presented is for only one pilot. However, the pilot has demonstrated in previous but different evaluation programs that his opinions are near the mean of opinions of several military pilots. Therefore, it is felt that generalizations from the data presented will not be greatly different from the opinions of a majority of military pilots.

Essentially, only the aircraft's short period frequency and damping have been varied. The pilot's comments, however, concern not only response time and motion but also stick forces, stick force gradient, stick motion, ability to trim the airplane and ability to track a target.

The pilot did four specific maneuvers for each configuration (each combination of f and ζ). He would comment on his likes and dislikes for a

configuration after each of the four maneuvers and then rate the configuration after completing all four maneuvers.

The specific maneuvers that were done are:

At 10, 000 ft. or starting at 10, 000 ft. altitude;

a. Trim the airplane in level flight at 200 mph indicated airspeed and fly for at least one minute. Note the ability to trim at the desired airspeed, ability to remain in trim, and any oscillatory motion.

b. From level flight at 200 mph indicated airspeed, make abrupt control steps to +1. 5g, +2g and +. 5 g absolute accelerations. Note airplane response time and any oscillatory motion.

c. From level flight at 200 mph indicated airspeed, make slow and rapid entries into level turns holding sight on horizon. Continue turns up to 180 degrees and note the ease and accuracy of tracking the horizon as affected only by use of the elevator control.

d. Slow airplane to 150 mph indicated airspeed and perform a gunnery run on a ground target. Note aircraft response time in the pushover, the ease and ability to track the target as affected only by use of the elevator control, and any oscillatory motion. Perform a constant g pullout. Note ability to hold g.

As mentioned, the pilot made comments after each maneuver of each configuration flown. Some comments on a number of particular items were desired for consistency of the comments, such that from the comments it would be possible to determine what the pilot was seeing and feeling and to determine those aspects of each configuration to which the pilot objected and those which he felt were good. The pilot frequently wished to make pertinent comments other than those which were specifically requested, and was encouraged to do so.

In order to insure having comments about a number of particular aspects a list was made and given to the pilot for each maneuver done, as follows:

Short Period Evaluation In-Flight Comments by Pilot in B-26

Maneuver Able (a) comment on:

1. Ability to trim
2. Stick forces

a) steady state

b) gradient (linearity)

c) centering force

3. Airplane response time
4. Airplane response motion
5. Feel of airplane

Maneuver Baker (b) comment on:

1. Stick forces
   a) steady state
   b) centering
2. Airplane responses
   a) response time
   b) response motion
3. Feel of airplane

Maneuver Charley (c) comment on:

1. Stick forces
   a) steady state
   b) gradient (linearity)
   c) centering forces
2. Airplane response
   a) to get on target (time and motion)
   b) while tracking (any oscillation?)
   c) during roll-out (time and motion)
3. Ability to track
4. Use of trim
5. Feel of airplane

Maneuver Delta (d) comment on:

1. Stick forces
   a) steady state
   b) gradient (linearity)
   c) centering

2. Response
    a) pushover 150 mph (time and motion)
    b) pullout 250 mph (time and motion)
3. Ability to track
4. Ability to hold load factor
5. Use of trim
6. Feel of airplane

All of the pilots' comments were recorded with a tape recorder.

After completing the evaluation maneuvers and comments on a configuration the pilot rated the configuration according to the following rating scale:

1. Optimum - This configuration is the best all around. It combines the best precision of control with the most comfortable control.
2. Acceptable Good - Noticeably better than acceptable but can be improved. For example, very comfortable to fly but not the best control precision.
3. Acceptable - In this configuration the airplane's mission can be accomplished reasonably well but only with considerable pilot effort and attention required directly for flying the airplane.
4. Acceptable Poor - The airplane is safe to fly but the required pilot effort and attention for just flying is such as to seriously reduce the effectiveness of the airplane as a tactical weapon.
5. Unacceptable - Pilot effort and attention for flying only is required to the extent that the airplane's usefulness as a tactical weapon is doubtful, or the airplane is unsafe if pilot attention is diverted from flying to navigation, radio use etc., or both.

The rating of each configuration was also recorded on the tape recorder.

The comments and the ratings were specified for a light bomber type of tactical airplane, and not fighters or heavy bombers. The pilot frequently would remark that the particular configuration would be suitable to some other specific type of airplane, but that it was not desirable for a B-26 type bomber. For example, a heavily damped slow responding configuration might be ideal for instrument or transport flying, but unacceptable for the maneuverability required of an attack bomber. He might also state qualitatively what

he would desire to make the configuration better for such a light bomber.

In giving the ratings for each configuration, the pilot very often was more definitive than the rating scale, and gave ratings with a plus or a minus. In addition, a marginal rating would sometimes be given, for example, "acceptable good to acceptable good minus". A rating of "optimum" was never given, since the pilot always felt that he might later be asked to evaluate something better. As a result, a 19 point scale was available to the pilot:

1. acceptable good plus
2. intermediate
3. acceptable good
4. intermediate
5. acceptable good minus
6. intermediate
7. acceptable plus
8. intermediate
9. acceptable
10. intermediate
11. acceptable minus
12. intermediate
13. acceptable poor plus
14. intermediate
15. acceptable poor
16. intermediate
17. acceptable poor minus
18. intermediate
19. unacceptable

Supplementary to the pilot's comments for each configuration, an oscillograph record was made of the aircraft's response to a step input to the elevator. These inputs caused a nose up pitch response from level flight and, by analyzing the records, the aircraft's undamped natural frequency f and damping ratio ζ are obtained for each configuration.

Some additional techniques which the pilot added that are worthy of noting

are:

In doing maneuver (a) (trim in level flight) the pilot would trim the aircraft, let it fly hands-off for approximately a minute and then further test the trim stability by pulsing the elevator control and noting the airplane response and tendency to return to the initial trim attitude. In maneuver (d) (ground gunnery run) he would pulse the elevator control after getting on the target and note the tendency of the aircraft to return to the target.

After doing any maneuver if the pilot felt he should repeat it for any reason at all, he would do so.

No tests were done in very turbulent air and if turbulent air was encountered the testing was discontinued until relatively smooth air was found, in order to have more consistent test conditions. Also the angle of attack sensing device that produces the α signal for the servo system is very sensitive to turbulence and, when large servo gains are used, large gusts would produce violent elevator motions. The absence of gusty air might have significant effects on the results.

Flight Calibration of Airplane Responses

For each configuration evaluated by the pilot and for an approximately equal number of additional calibration points, oscillograph records were taken of α, $\dot{\alpha}$, n_z, F_s, δ_s, and δ_e in an incremental 0.5 g pullup. These pullups were initiated by holding an out-of-trim force at 200 mph and suddenly releasing the stick.

By techniques which assume that the modified airplane response is that of a linear second order system the angle of attack records and the normal acceleration records were analyzed for the undamped natural frequency and damping ratio of the airplane-servo system combination. Particularly at high damping ratios (ζ near 1.0), the accuracy of the analysis of the records was reduced. It was attempted to fair, by eye, through the flight test points, lines of constant frequency and lines of constant damping ratio, as a function of the sensitivities of the two inputs (δ_e/α and $\delta_e/\dot{\alpha}$) used to control these two parameters. However, doubt existed as to the accuracy of this

grid, due primarily to the reduced accuracy in data reduction mentioned above. It was obvious, however, that the shape of the grid was not similar to that of Figure 6, theoretically calculated with no servo lags. Therefore, equations were set up which included approximations to the known lags of the artificial stability system. A grid of frequency and damping ratio as a function of δ_e / α and $\delta_e / \dot{\alpha}$ was calculated from these equations. This grid is shown in Figure 7 and the equations are shown in detail in the Appendix. This calculated grid, including lags, agreed quite well with the experimental points. For additional refinement of the grid, the differences between the f and ζ values determined from the flight transients and determined from the calculated grid (Δf and $\Delta \zeta$) were tabulated for each point. These differences were plotted as a function of f and ζ and of δ_e / α and $\delta_e / \dot{\alpha}$, to see if they tended to be random, or if they contained any significant systematic errors. Empirically it seemed that these differences could be reduced if the grid were altered as a linear function of f and ζ. The result would be to shift and rotate the grid slightly. A better choice of system lags and airplane characteristics could reasonably explain the indicated changes. Therefore, corrections to Figure 7 of the following form were assumed:

$$\Delta f = C_0 + C_1 f + C_2 \zeta$$

$$\Delta \zeta = C_3 + C_4 f + C_5 \zeta$$

The three constants C_0, C_1, and C_2 were determined by a three-dimensional linear least-squares fit of the tabulated values of Δf. C_3, C_4, and C_5 were similarly determined by fitting the tabulated values of $\Delta \zeta$ A recalculated grid was then constructed, using the results of these two least-squares analyses (Figure 8). This grid proved to be satisfactory for predicting f and ζ for each combination of δ_e / α and $\delta_e / \dot{\alpha}$ sensitivities. The uncertainty in predicting f and ζ are still largest at higher values of ζ, especially $\zeta > 1.0$, but tend to be normally distributed.

Figure 9a is a plot of all the pilot evaluated points. Figure 5 is a fairing

of the points of Figure 9a. To simplify visual fairing of the points, Figure 9b contains only the highest and lowest of the four ratings.

The Data and its Analysis

The data collected in these evaluations consisted of the pilot's comments and his ratings, together with the calibration records. The following is a dicussion of the comment data only.

In an attempt to group the data from the 19 point rating scale described previously and to determine why the pilot gave his ratings, the comments for all configurations which were given the same rating were compiled and studied for consistent remarks. Such a qualitative means of comparison proved very weak for determining precisely what factors caused the pilot to rate certain configurations as he did. Therefore, a numerical rating scale was devised as follows. A number from 1 to 4 was assigned to each item upon which the pilot commented for each maneuver and for each configuration. These numbers were derived from the comments, the higher the number the more objectionable the characteristic commented upon.

Numerical averages were obtained for each maneuver, for each configuration, and for each rating class (e.g. AG^-). Also the standard deviations were estimated for each rating class. Comparisons of these averages and their standard deviations for each rating class indicated that significant differences existed between some adjacent ratings, but that essentially no differences existed between others. Therefore, some of the ratings were combined. The outcome of this grouping is to reduce the number of rating classes to four in the following manner:

PILOT'S RATINGS	SYMBOLS	RATING CLASS
ACCEPTABLE GOOD PLUS TO ACCEPTABLE GOOD	AG^+ - AG	1 BEST TESTED
ACCEPTABLE GOOD	AG	
ACCEPTABLE GOOD TO ACCEPTABLE GOOD MINUS	AG - AG^-	
ACCEPTABLE GOOD MINUS	AG^-	2 GOOD
ACCEPTABLE GOOD MINUS TO ACCEPTABLE PLUS	AG^- - A^+	
ACCEPTABLE PLUS	A+	
ACCEPTABLE PLUS TO ACCEPTABLE	A^+ - A	
ACCEPTABLE MINUS	A^-	3 FAIR
ACCEPTABLE MINUS TO ACCEPTABLE POOR PLUS	A^- - AP^+	
ACCEPTABLE POOR	AP	
ACCEPTABLE POOR MINUS	AP^-	4 POOR
UNACCEPTABLE	U	

This grouping does not by itself explain the differences among its members. Generally, the differences are attributed to changes in apparent stick forces, response time and response motion, each of which has its individual effect on the pilot's ability to track a target and to fly the airplane.

Arbitrarily, but for the sake of clarity, these four groups have been labelled (1) best tested (2) good, (3) fair, (4) poor. The individual test points plotted in Figure 9a are divided into these four groups. Figure 5 is a fairing of the points in Figure 9a. Note that the areas are not closed, but are open toward the high damping and high frequency regions.

Studying the comments associated with the various areas of Figure 5 resulted in Figure 10. This figure gives a pictorial presentation of the reasons why the pilot rated configurations as he did.

Only two types of comments indicated an approach to a "dangerous" configuration, as might describe the "minimum flyable" boundary mentioned in the introduction. These were the "dangerous oscillations" at low ζ $(\zeta < .20)$ around $f =$ .4 cps, and the "fear of gusts" comments around $\zeta = .3$ and $f =$ .6 cps. Otherwise no data were obtained on "minimum flyable" boundaries.

Figure 10 also points out how to theoretically reproduce the areas of Figure 5. This process is attempted below. The results are hypothetical, but are of sufficient interest to discuss in more detail.

The prevalent comments in Figure 10 will be itemized individually. The purpose is to determine what parameters might have provoked a given comment, and how that parameter varies as f and ζ are varied.

Figure 11 shows a typical normalized theoretical second-order curve. This corresponds closely to the α response to an elevator step input. Four of its more meaningful parameters which might affect pilot opinions are noted, rise time to .5 of steady state (t_R), time for the envelope to settle to .9 of steady state (t_S), the peak ratio $(P.R.)$, and the second derivative at zero time $(\ddot{\alpha}_S / \alpha_{SS})$. Since at zero time, $\ddot{\alpha} \approx \ddot{\theta}$ *, this fourth parameter can be referred to as intitial pitch acceleration $(\ddot{\theta}_0)$. The ratio $\ddot{\theta}_0 / F_S$ is considered to be a measure of the sensitivity for small disturbances around trim.

Plots of these four parameters t_R, t_S, $P.R$, and $\ddot{\theta}_0 / F_S$ as a function of f and ζ are shown in Figure 12. The actual $\ddot{\theta}_0 / F_S$ curves are different from the theoretical second order curves because of servo lags.

The comments pertaining to response time, i.e. "sluggish" or "response too fast" probably are related to rise time. The "heavy forces" and "light forces" comments are possibly functions of t_R also, although $\ddot{\theta}_0 / F_S$ is a measure of "centering" forces around trim. When the response in a pull-

* $\ddot{\alpha} = \ddot{\theta}$ *immediately after application of a step elevator only if the effects of* $C_{L_{\dot{\delta}}}$ *are neglected. For the B-26 test configuration, this difference between* $\ddot{\alpha}_0$ *and* $\ddot{\theta}_0$ *amounts to less than 1%.*

up is too fast, the pilot tends to slow it up by releasing some of the initial control force, thus giving rise to "light forces". A slow response gives the opposite result.

Due to the system lags, the lines of constant $\ddot{\theta}_0 / F_s$ tend to be parallel to the lines of constant t_R instead of being horizontal (Figures 12a and 12d). As a result, in the direction of increasing f and decreasing ζ, the tests unfortunately do not show whether the pilot objects to decreasing t_R or increasing $\ddot{\theta}_0 / F_s$. If $\ddot{\theta}_0 / F_s$ were the objectionable parameter, and if the system lags could be reduced, then the open areas of Figure 5 would tend to be closed by the more nearly horizontal lines of constant $\ddot{\theta}_0 / F_s$. The "fear of gusts" comment in Figure 10 is associated with a high $\ddot{\theta}_0 / F_s$ and small t_R. The pilot-induced oscillations at higher frequencies and ζ around .5 are probably caused by a short rise time coupled with pilot lags such that the pilot gets out of phase with the rapidly responding airplane. The oscillatory areas are essentially a function of peak ratio where moderate and large overshoot are readily apparent although frequency is somewhat of a parameter. The "sluggish and oscillatory" region gives rise to comments such as "motion appears like a short phugoid or roller coaster". Settling time is probably a good measure of this characteristic. The "dangerous oscillations" are likely a function of both peak ratio and rise time. Here the pilot transfer function is of predominant influence.

The theoretical curves from Figure 12 are combined in Figure 13, and superimposed on the boundaries from Figure 5. Thus, the "best tested" area could be defined as a rise time of about .45 sec, with the settling time less than 2.25 sec, and a peak ratio less than .23. The "poor" boundaries are approximately bounded by t_R = .35 and t_R = .8, and $P.R.$ = .6. The "minimum flyable" boundary could not be accurately determined, but the general location is shown in Figure 13. The comments indicate it is a function of both $P.R.$ and t_R.

In summary, the ratings from the one pilot, for variable short period characteristics, were consistent. The pilot's likes and dislikes were a function of both frequency and damping. The response became unsatisfactory if the overshoot were too pronounced, if the rise time were too short or too long, and

if the settling time were too long. A "best tested" area of combinations of f and ζ was determined. A "minimum flyable" region of too low damping and too high frequency was indicated but not accurately located.

PHUGOID EVALUATIONS

Flight Calibrations and Contact Flight Evaluations

Flight calibrations consisted of manually disturbing the airplane from trim airspeed and recording the resulting hands-off phugoid oscillation. The nose was displaced gradually until the airspeed was off about 20 mph from trim, and the elevator was released. A 5 mph initial out-of-trim, airspeed was used for the negatively damped points. Records showed that the combination of friction and small α changes prevented the elevator from floating during these calibration maneuvers. Figure 14 shows a plot of the period and damping ratio as functions of sensitivities of u and $\dot{u}$ inputs to the auxiliary surface. As opposed to the short period calibrations where a large number of transients showed no overshoot, the phugoid range investigated is more lightly damped, and only in a very few extreme cases could the peaks not be measured accurately. Lines of constant period and damping ratio were faired by eye from the measured points directly as shown in Figure 14.

Evaluations of variable phugoid characteristics were commenced by having the pilot fly 15 to 30 minutes of contact flight at each of several values of phugoid period and damping, and ratings of the acceptability of each configuration were obtained. On flight 8, for instance, the pilot was given the following two configurations:

(1) $T = 60\ \text{sec},\ \zeta = +.32$

(2) $T = 76\ \text{sec},\ \zeta = -.12$

The pilot commented that the change in phugoid damping was very obvious if the airplane were allowed to oscillate freely. He suspected that his ability to maintain trim during simulated instrument flight under contact conditions may have been slightly improved with the higher damping, but no marked difference existed between the two configurations. Therefore, evaluations of the phugoid under contact conditions were discontinued.

Description of Simulated Blind Flights and Presentation of Data

A type of blind flying hood developed by the USAF Tactical Air Command at Langley Field, Virginia, was built and installed in the test airplane. This is a shutter type hood, which completely shields the horizon from the pilot, but allows the co-pilot good visibility. The pilots considered that this hood gave a better blind flying simulation than did the use of windshield and goggles of complementary colors.

Courses on civil airways were laid out and, on each of several flights, the pilot evaluated 3 different damping configurations. Time histories of airspeed and altitude were recorded as a measure of how well the pilot flew a constant airspeed and altitude during simulated blind flying conditions. Each configuration was flown for 30 minutes, and the flight plan was arranged so that the number of airway intersections, turns, and radio checks were about equal for each run. The runs were made 30 minutes in an attempt to make the pilot effort random. The pilot could easily concentrate for short periods of up to 5 minutes, and overcome any deficiencies in the phugoid. However, the navigation duties and radio checks tended to use up any excess concentration during the longer runs. In addition, an attempt was made to keep the terrain similar in order to average the variable gustiness of the atmosphere. Also "out and back" flight paths were covered for the same reason.

The purpose of the quantitative measurements was to see if there was a difference in the ability to hold a trim airspeed and altitude with variations in phugoid characteristics, aside from any differences which the pilot might observe. An attempt would be made to correlate the quantitative measurements with the pilot ratings. It was further decided to concentrate on varying the phugoid damping at essentially a constant period, since it was believed that the effects of damping would be greater than the effects of period.

Under the simulated blind flying conditions, it became immediately obvious that the pilot was quite sensitive to changes in phugoid damping. He gave comparative ratings for each run at the conclusion of the flight. The time histories for the 30 minute runs were reduced to the autocorrelation functions

and the power spectral densities for the altitude and airspeed. The pilot ratings, together with the power spectral densities of the altitude and airspeed, when correlated with the damping ratio of the phugoid, constitute the data.

The following table lists the data presented. The pilot comments for each of the flights immediately follow the table. Pilot ratings were obtained for all runs.

FLIGHT	RUN	DAMPING RATIO	ALTITUDE POWER SPECTRAL DENSITY	AIRSPEED POWER SPECTRAL DENSITY
50	1	-.04	Fig. 15	NONE
	2	+.28	Fig. 15	NONE
	3	+.05	NONE	NONE
74	1	+.28	Fig. 16	Fig. 17
	2	-.15	Fig. 16	Fig. 17
	3	+.05	Fig. 16	Fig. 17
	4	+.05	Fig. 16	Fig. 17
78	1	-.15	Fig. 18	Fig. 19
	2	-.15	Fig. 18	Fig. 19
	3	-.15	Fig. 18	Fig. 19
80	1	-.02	Fig. 20	Fig. 21
	2	+.10	Fig. 20	Fig. 21
	3	+.05	Fig. 20	Fig. 21

FLIGHT NO.: 50 (11/20/53)
DURATION: 2:35

PILOT'S REPORT

The purpose of this flight was further evaluation of the phugoid characteristics of the aircraft for different settings of the auxiliary surfaces. During a round robin, under-the-hood flight from Buffalo to Elmira, Syracuse and return, via the same route, three different settings were given to the pilot for his evaluation. Comments on these three settings are as follows:

Setting #1 was hard to fly in that the aircraft seemed to deviate from trimmed out altitude at frequent intervals, and close attention of the elevator control was required by the pilot. Since some time had elapsed since the pilot had flown a previous test of this type, some of the difficulty of holding altitude was attributed to the pilot being a little rusty on instrument flying. However, even after taking this fact into consideration the pilot felt that the aircraft was difficult to hold at a given altitude.

Setting #2 seemed to be very good in that the pilot was able to hold altitude reasonably well after trimming out the aircraft. Most of this portion of the flight was made with the pilot making occasional correction by use of the elevator trim control only.

Setting #3 was found to be unstable longitudinally when it was first set up but as the flight progressed the pilot was able to fly the aircraft within fairly close altitude tolerances. This may have been due to the pilot suddenly being required to fly a slightly unstable configuration after having flown a stable one: and the fact that it seemed better as the flight progressed may be due to the pilot improving his technique.

The three settings flown are rated as follows:

#1 the worst of the three flown
#2 the best of the three flown
#3 intermediate of the three flown.

COMMENTS;

The damping ratios evaluated on this flight were:

(1) -.04

(2) +.28

(3) +.05, the normal airplane without artificial stability.

The photo observer camera ran out of film during the third run. Therefore, the power spectral density of the altitude of only the first two runs are presented in Figure 15. The airspeed time histories for this flight were not analyzed.

FLIGHT NO.: 74 (5/6/54)

DURATION: 2:25

PILOT'S REPORT:

The purpose of this flight was to evaluate three different configurations of phugoid damping. Each configuration was flown under the hood, simulating instrument flight for about thirty minutes per run. The phugoid characteristics of the aircraft were varied by the auxiliary surfaces located under the horizontal stabilizers. The pilot was informed each time the phugoid damping was changed but was not informed whether it was normal, less damped, or more heavily damped than the normal airplane.

The first configuration was flown at an altitude of 8,000 ft. and an airspeed of 200 mph. The course was from Buffalo to Elmira. Air conditions were turbulent but in spite of this the pilot managed to hold altitude within plus or minus 100 ft. This was also the first part of the test and the pilot had not flown under the hood for some weeks, which would indicate that he might be a little rusty. This configuration was judged to be good with regard to phugoid characteristics.

The second configuration was flown at 10,000 ft and 200 mph. The altitude was increased due to a rising cloud deck. Flight course was from Elmira to Buffalo. Air turbulence was slightly worse than on the first leg but the pilot now had the benefit of thirty minutes practice. The pilot advised the flight crew in the early part of this run that the phugoid characteristics were bad. The tendency for the increase of amplitude and rate of divergence from the flight altitude, once the aircraft had been disturbed, was easily recognized

The third configuration was flown at 4000 ft. and 200 mph. The flight course was from Buffalo to Rochester and return. Air turbulence was very heavy. The pilot found this configuration to be good but altitude change was as much or plus or minus 200 ft. due to the severe turbulence.

In summary the pilot rates the three configurations as follows: Number 1 - best, Number 2 - bad, Number 3 - good.

COMMENTS:

The damping ratios evaluated on this flight were:

(1) +.28

(2) -.15

(3) +.05, the normal airplane without artificial stability.

The third 30 minute run was analyzed as two 15 minute runs. The power spectral densities of altitude and airspeed variations are shown in Figures 16 and 17.

FLIGHT NO.: 78
DURATION: 2:30

PILOT'S REPORT

This was a simulated (under the hood) instrument flight from Buffalo to Elmira, to Syracuse and return. Flight altitude was 4, 000 ft., airspeed 200 mph and air turbulence was medium to heavy.

Three configurations of phugoid damping were introduced into the aircraft through the auxiliary surfaces located under the horizontal stabilizer. The pilot flew each configuration for a thirty minute period to evaluate its characteristics. He was informed each time the configuration was changed but was not informed as to its damping characteristics. The pilot judged the three configurations as follows: #1, poor damping; #2, fair damping; #3, medium poor to medium fair damping. The pilot believes that all three configurations were less damped than the normal airplane. During this flight as well as all previous flights of this nature, the pilot attempted to fly the airplane in a relaxed manner using the trim as much as possible and attending to radio procedure and manual procedure as necessary. The pilot did not attempt to hold altitude to the exclusion of other instrument flight functions.

COMMENTS:

Unknown to the pilot, each of the three configurations were identical, with a phugoid damping ratio of -.15. The purpose was to check the repeatability of the quantitative data and the pilot ratings. The power spectral densities of the altitude and airspeed variations are shown in Figures 18 and 19.

FLIGHT NO.: 80
DURATION: 2:35

PILOT'S REPORT

This was a round robin simulated instrument flight (under the hood) from Buffalo, to Elmira, to Syracuse and return. Flight altitude was 4,000 ft. and airspeed was 200 mph.

During the flight, three different configurations of phugoid damping were introduced into the airplane through the use of the auxiliary surfaces located beneath the horizontal stabilizers. The pilot was advised each time a new phugoid configuration was set up for his evaluation, but was not advised what its characteristics were. Between each configuration, a short period was spent flying the normal airplane. The pilot evaluated the three configurations checked as follows: #1, slightly less damped than the normal airplane; #2, normal airplane; #3, slightly more damped than the normal airplane. These damping settings are all closer to the normal airplane than the previous flight. Air conditions were fairly turbulent.

COMMENTS:

The increments of phugoid damping were quite small on this flight. The damping ratios evaluated were:

(1) -.02

(2) +.10

(3) +.05

The power spectral densities of the altitude and airspeed variations are shown in Figures 20 and 21.

Discussion of Phugoid Data

When given large increments of ζ in one flight, the pilot accurately rated the runs according to ζ. In both Flights 50 and 74, the pilot rated 3 runs, the desirability increasing as ζ increased. During Flight 78, all 3 configurations were the same negative value of ζ and were rated as poor. The pilot did attempt to differentiate, but noted all three were worse than the normal airplane. For Flight 80, considerably smaller increments were used. The pilot rated the +5% and +10% points in the wrong order, but correctly rated the -2% as the worst of the three. The pilot did not feel that he could compare runs from one flight to another. However, he correctly stated that all configurations in Flight 80 were more highly damped than all configurations in Flight 78.

The data indicate that the effects of phugoid damping variations are quite subtle. The pilot ratings showed good correlation with phugoid damping, showing increased ease of flying with increased damping. However, the pilot was often prone to attribute his observed differences to factors other than phugoid damping, if possible, such as lack of practice of instrument flight procedures or variable gustiness.

There is good correlation within any one flight between damping ratio and the magnitude of the power spectral density plots, especially the magnitude at the phugoid frequency (.02 cps). The altitude variations have a more consistent correlation than does the airspeed. The pilots expect this, explaining that, when entering up-drafts and down-drafts, elevator trim is adjusted to keep the prescribed altitude, but no power adjustments are made. Thus the airspeed would wander more than the altitude due to pilot technique. In Flight 80, the magnitudes of the power spectral density plots correlate with the pilot opinions better than either the power spectral density magnitudes or the pilot opinions correlate with damping ratio. This is not considered significant due to the small changes in damping ratio which existed during this flight.

For each damping ratio for which repeat runs are available from different flights, the altitude power spectral densities are re-plotted. These plots are shown in Figures 22, 23 and 24 for ζ = -.15, +.05, and +.28 respec-

tively. The purpose of these plots is to check the consistency of the measurements from day to day since it is possible that the effects of air turbulence could be quite different. The variations are more than in Flight 78 (Figure 18), where the value of the damping was the same for all three runs during the flight. However, the differences are not as large as during those flights in which the incremental variations of damping ratio were large. As a result of these observations, Figure 25 was plotted. The magnitude of the altitude power spectral density at .02 cps (phugoid frequency) is plotted vs. damping ratio for all 12 points from 4 different flights. The best straight line on this semi-log plot is determined by least squares for the 12 points. The line shows a definite trend of lower magnitudes of altitude variation for higher damping ratios. This plot, together with the pilot ratings within each flight, show that phugoid damping has an important effect on the pilot's ability to maintain instrument flight under specified altitude and airspeed conditions. However, with the test method used, the data does not show that reliable results could be obtained when comparing configurations whose damping ratios do not differ by more than .10. The estimated standard deviations, as noted on Figure 25, are determined from the 12 points. The two damping ratios where the standard deviations are noted indicate that about .10 is the minimum incremental damping for which changes in altitude power spectral density could be accurately measured.

In summary, the test method showed that a relation exists between phugoid damping and the pilot's rating of how difficult is it to maintain a simulated blind flight plan. Also, the magnitude of power spectral density of the altitude and airspeed variations (especially the altitude) in simulated blind flight are related to the phugoid damping. The precision of the tests and the quantity of data were not sufficient to define acceptable and optimum boundaries of phugoid damping.

CONCLUSIONS AND RECOMMENDATIONS

It is concluded that:

1. Consistent pilot ratings of various values of short period frequency and damping ratios were obtained. A "best tested" area of combinations of f and ζ was determined. Boundaries between areas of different ratings were determined.
2. Short period ratings were a function of both frequency and damping. As expected, the pilot objected to too little damping. In addition, the pilot's opinion was that too much damping or too low an undamped frequency resulted in a response that was objectionably slow. Also, increasing the frequency at a particular damping ratio can result in too fast a response and a corresponding decrease in pilot ratings. Ratings of "dangerous to fly" were indicated if the damping were too low or the frequency too high, or both.
3. A correlation between phugoid damping and the pilot's ratings was shown for instrument flight conditions, the pilot preferring higher damping ratios. Also a correlation between phugoid damping and the pilot's measured ability to maintain altitude and airspeed during instrument flight was determined. However, no boundaries of the pilot's ratings for phugoid damping were determined.

It is recommended that:

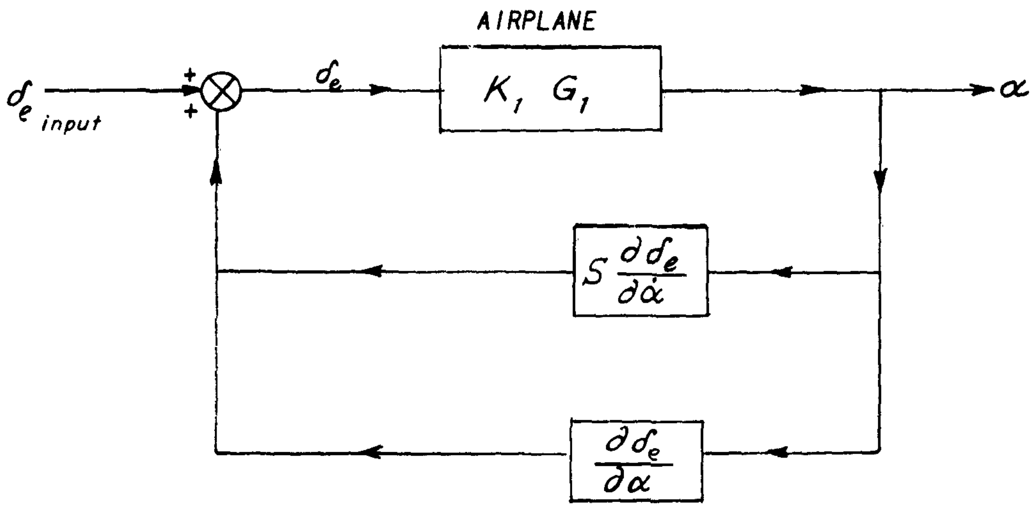
1. The short period ratings should be verified in rough air.
2. The short period ratings established by one pilot should be verified by a limited number of additional pilots.
3. The phugoid evaluations should be extended and refined to determine quantitative boundaries of pilot acceptance.

APPENDIX

Calculated Frequency and Damping, Including Servo Lags, of Short Period for B-26

In Reference 2, equations (18) and (19) give the elevator sensitivities required for α and $\dot{\alpha}$ inputs to give a desired frequency and damping of the short period. Using these equations and basic airplane parameters as given in Reference 2 for the B-26 at 200 mph indicated airspeed, 10, 000 ft. altitude, and 0.11 static margin, values of $\delta e / \alpha$ and $\delta e / \dot{\alpha}$ were calculated to give a range of short period characteristics. These values are plotted in Figure 6.

These calculations correspond to a block diagram as shown below and include no lags of the control equipment.



BLOCK DIAGRAM-NO SERVO LAGS

where $K_1 G_1 = \alpha / \delta_e$ of the airplane in maneuvering flight,

$$K_1 = \frac{-C_{m_{\delta_e}}}{C_{m_\alpha} + \frac{C_{L_\alpha} C_{m_q}}{2\mu}} = -1.887$$

G_1 = calculated short period dynamics of the basic airplane without artificial stability

$$= \frac{1}{(S/\omega)^2 + 2\zeta S/\omega + 1}$$

S = Laplace differential operator

Frequency responses of components taken on the ground, and calibration transients taken in flight indicated the effects of system lags were large, particularly at larger values of ω and ζ.

Considerations of measured responses indicated that three distinct lags were important:

1. lags due to the elevator servo dynamics
2. lags due to the dynamics of α differentiator (to obtain $\dot{\alpha}$ signal)
3. lags due to the pitch rate component in angle of attack pickup due to the distance of pickup forward of the cg.

Considering the elevator servo, transient responses to step inputs were taken in flight and on the ground at different amplitudes and both up and down deflections. Figure 20 in Reference 4 gives a frequency response for the servo. A second order response of the form

$$\frac{\delta_e}{E_i} = \frac{K}{(S/\omega)^2 + 2\zeta S/\omega + 1}$$

was fitted to the frequency response, the values determined being

$$\omega = 13.2 \text{ rad/sec } (2.1 \text{ cps})$$

$$\zeta = .56$$

The angle of attack differentiator consists of a small position servomotor positioned by an autosyn driven by an angle of attack vane, the servomotor driving a rate generator. The output of the rate generator was used as the $\dot{\alpha}$ signal source and fed to the elevator servo. Reference 4 describes the com-

ponents more completely. The frequency response of this servo was approximated by the form:

$$e_2/\alpha_V = S K_2 G_2$$

$$K_2 = \frac{\delta_e}{\dot{\alpha}_V}$$

$$G_2 = \frac{1}{(S/\omega)^2 + 2\zeta S/\omega + 1}$$

$$\omega = 18.8 \text{ rad/sec } (3.0 \text{ cps})$$

$$\zeta = .50$$

To compute the lag due to the pitch rate component the following equations were used, including the flight determined position error:

$$\alpha_V = (\alpha_V/\alpha)_{position\ error}\ \alpha - \dot{\theta}\frac{\ell_V}{U}$$

$$\dot{\alpha} - \dot{\theta} = -\frac{C_{L\alpha}}{2\tau}\alpha$$

or

$$\alpha_V = \left(\frac{\alpha_V}{\alpha} - \frac{C_{L\alpha}}{2\tau}\frac{\ell_V}{U} - \frac{\ell_V}{U}S\right)\alpha$$

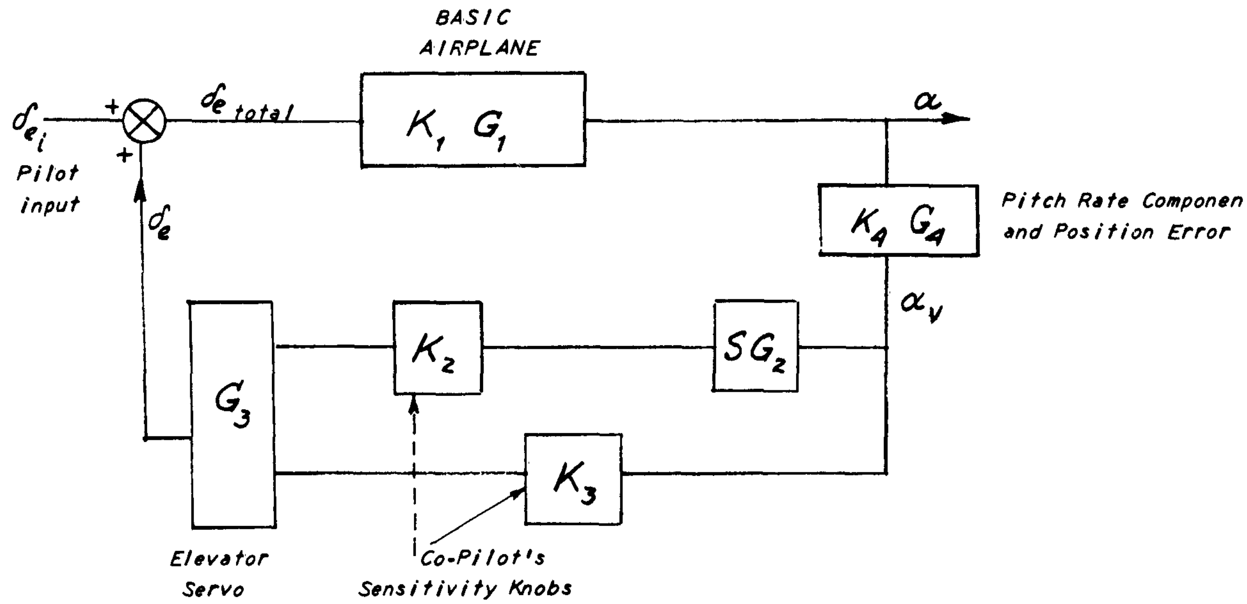
$$= K_4 G_4 \alpha$$

$$K_4 = \frac{\alpha_V}{\alpha} - \frac{C_{L\alpha}}{2\tau}\frac{\ell_V}{U}$$

$$G_4 = 1 - aS$$

$$a = \frac{\ell_V/U}{\frac{\alpha_V}{\alpha} - \frac{C_{L\alpha}}{2\tau}\frac{\ell_V}{U}}$$

The closed loop then becomes:



BLOCK DIAGRAM INCLUDING LAGS

$$\alpha = K_1\, G_1\, \delta_{e\,total}$$

$$\delta_{e\,total} = \delta_{e_i} + G_3 (K_3 + SK_2\, G_2)\, K_4\, G_4\, \alpha$$

or

$$\frac{\alpha}{\delta_{e_i}} = \frac{K_1\, G_1}{1 - K_1 G_1 G_3 (K_3 + SK_2\, G_2) K_4 G_4}$$

Then clearing fractions for transfer functions with denominators:

$$\frac{\alpha}{\delta_{e_i}} = \frac{K_1 (G_2 G_3)^{-1}}{(G_1 G_2 G_3)^{-1} - K_1 K_2 K_4 G_4 S - K_1 K_3 K_4 G_4 (G_2)^{-1}}$$

The denominator can be expanded into a sixth order equation in S and including the two variables K_2 and K_3

$$Denom. = S^6 + AS^5 + BS^4 + CS^3 + AS^2 + ES + F \tag{1}$$

where

$$A = A_1$$

$$B = B_1$$

$$C = C_1 + C_3 K_3$$

$$D = D_1 + D_2 K_2 + D_3 K_3$$

$$E = E_1 + E_2 K_2 + E_3 K_3$$

$$F = F_1 + F_3 K_3$$

where $A_1, B_1, C_1, D_1, E_1, F_1,$ are the coefficients of the 6th order resulting from expanding $(G_1 G_2 G_3)^{-1}$.

Assuming K_2 and K_3 are set to give a desired short period root, the 6th order can also be factored:

$$Denom. = (S^2 + 2\zeta_{SP}\omega_{SP} S + \omega_{SP}^2)(S^4 + aS^3 + bS^2 + cS + d) \tag{2}$$

Multiplying out and equating (2) to (1) above gives:

$$A_1 = a + 2\zeta_{SP}\omega_{SP} \tag{3a}$$

$$B_1 = b + a2\zeta_p \omega_p + \omega_{SP}^2 \tag{3b}$$

$$C_1 + C_3 K_3 = c + b2\zeta_{SP}\omega_{SP} + a\omega_{SP}^2 \tag{3c}$$

$$D_1 + D_2 K_2 + D_3 K_3 = d + C2\zeta_{SP}\omega_{SP} + b\omega_{SP}^2 \tag{3d}$$

$$E_1 + E_2 K_2 + E_3 K_3 = d2\zeta_{SP}\omega_{SP} + C\omega_{SP}^2 \tag{3e}$$

$$F_1 + F_3 K_3 = d\,\omega_{SP}^2 \tag{3f}$$

Eliminating the four extraneous variables, a, b, c and d these six equations are solved simultaneously for K_2 and K_3 thus giving the sensitivities to give the assumed period and damping:

$$a = A_1 - 2\zeta\omega$$

$$b = B_1 - a\,2\zeta\omega - \omega^2$$

$$c = C_1 - b2\zeta\omega - a\omega^2 + C_3 K_3$$

$$d = 1/\omega^2 F_1 + F_3/\omega^3 K_3$$

Substituting these four equations into (3d) and (3e) gives

$$\left\{ \begin{array}{l} D_2 K_2 + H_1 K_3 = H_3 \\ E_2 K_2 + H_2 K_3 = H_4 \end{array} \right\}$$

where

$$H_1 = D_3 - C_3 2\zeta\omega - F_3/\omega^2$$

$$H_2 = E_3 - C_3\omega^2 - F_3/\omega^2\, 2\zeta\omega$$

$$H_3 = -D_1 + b\omega^2 + (C_1 - a\omega^2 - b2\zeta\omega)2\zeta\omega + F_1/\omega^2$$

$$H_4 = -E_1 + (C_1 - a\omega^2 - b2\zeta\omega)\omega^2 + F_1/\omega^2\, 2\zeta\omega$$

Then

$$K_2 = \frac{H_3 H_2 - H_1 H_4}{D_2 H_2 - H_1 E_2}$$

$$K_3 = \frac{D_2 H_4 - E_2 H_3}{D_2 H_2 - H_1 E_2}$$

Figure 7 results from these calculations.

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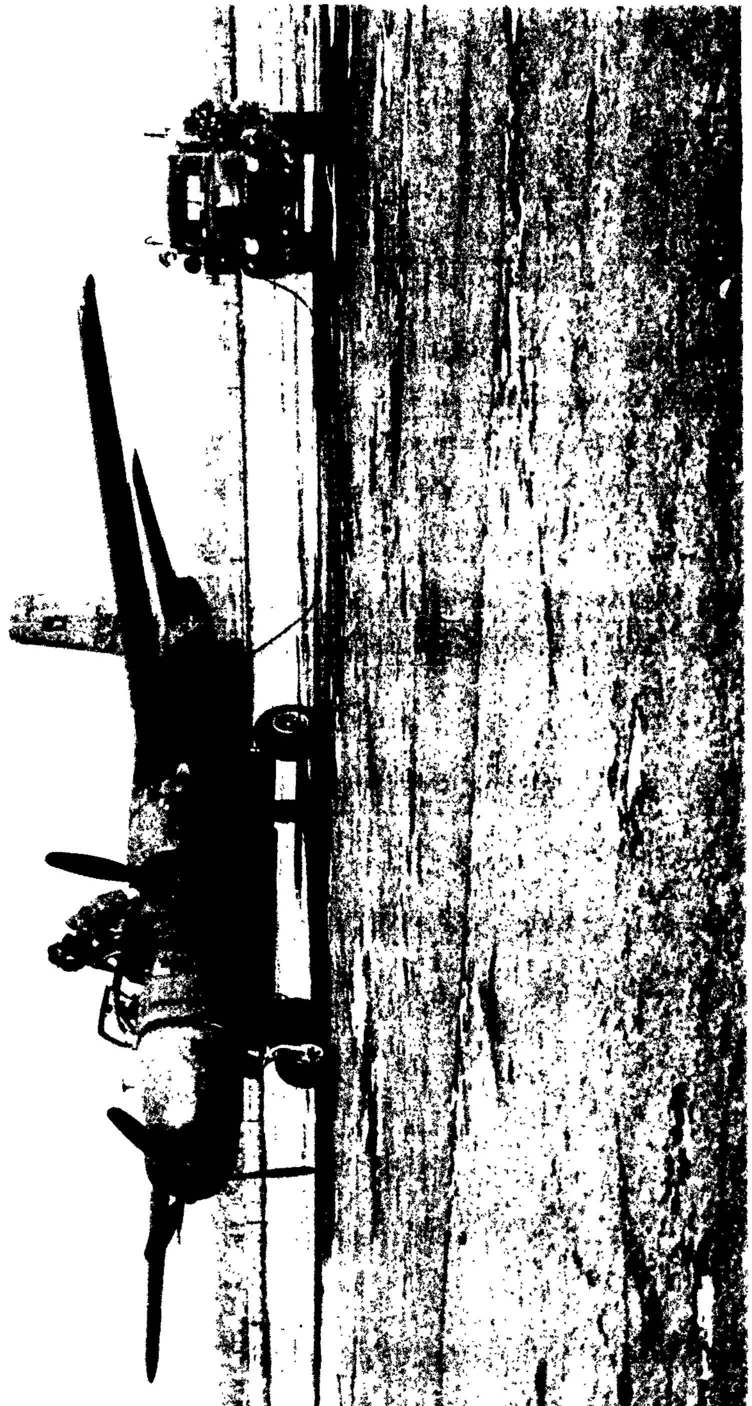

FIGURE 1 B-26B SERIAL NO. 44-34653

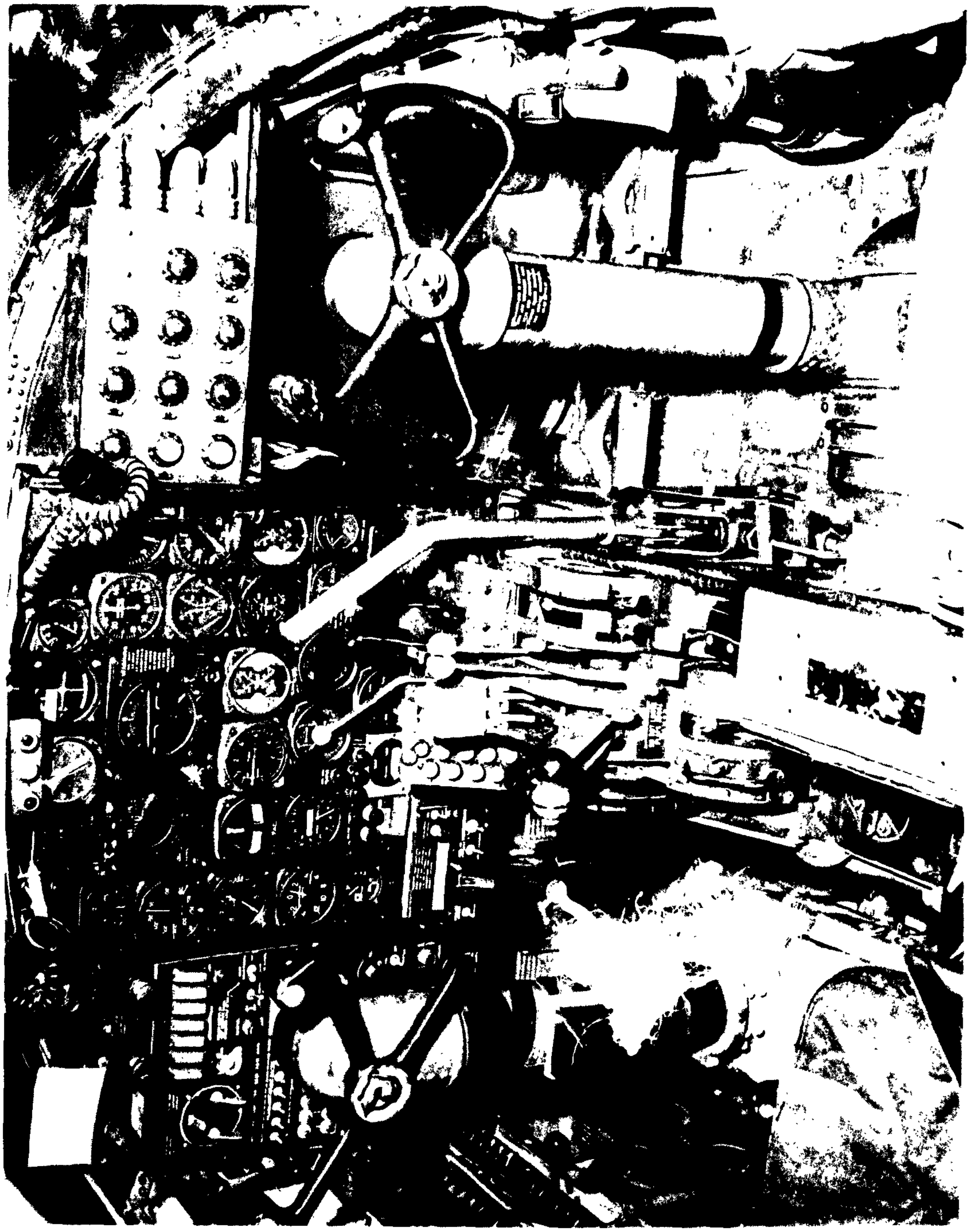

FIGURE 2 CO-PILOT CONTROL PANEL

FIGURE 3   AUXILIARY PITCHING SURFACE

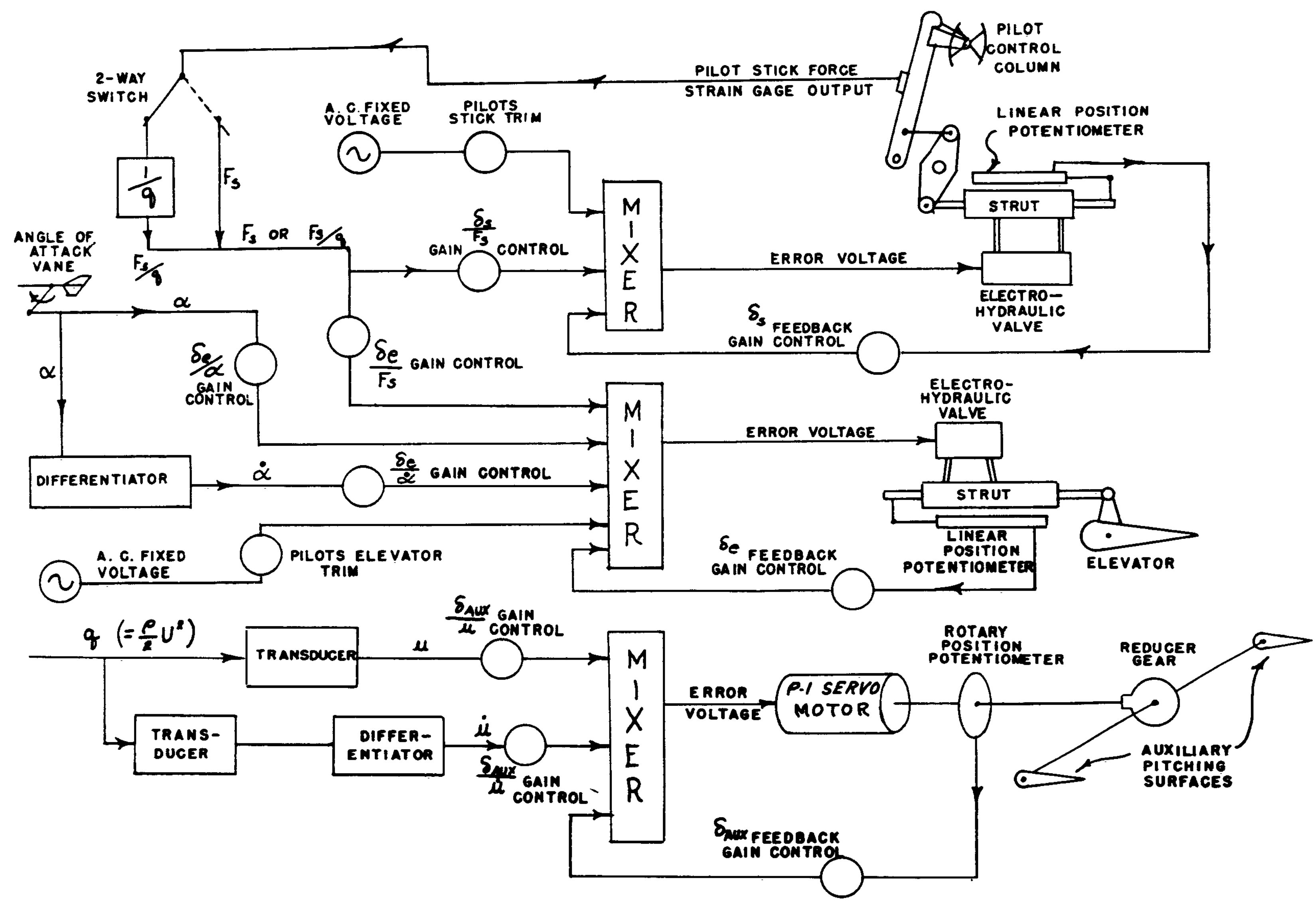

FIGURE 4 SCHEMATIC OF B-26 VARIABLE STABILITY CONTROL SYSTEM

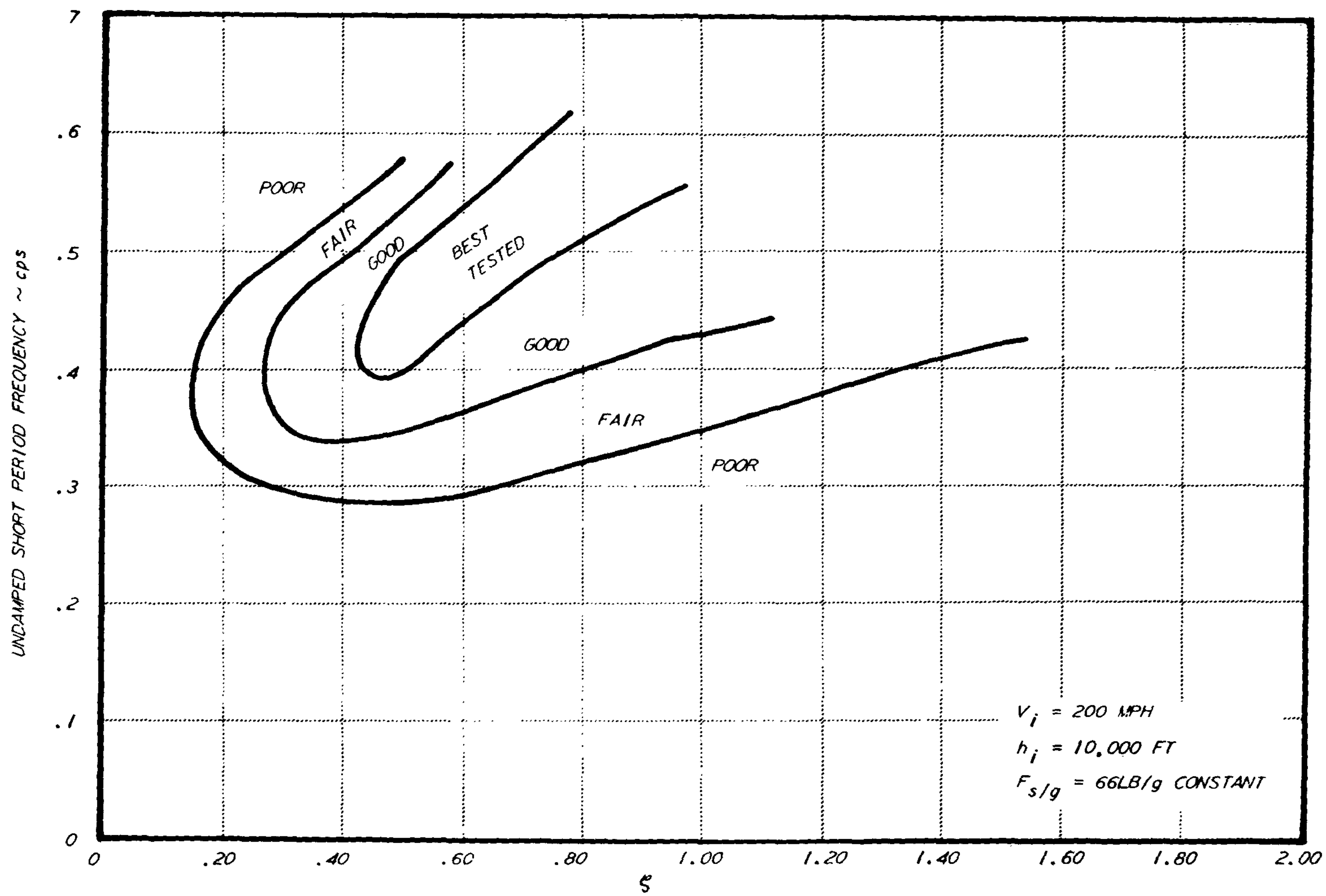

FIGURE 5 FAIRED CURVE OF PILOT ACCEPTANCE OF A B-26 WITH VARIOUS SHORT PEROID UNDAMPED FREQUENCY AND DAMPING RATIO

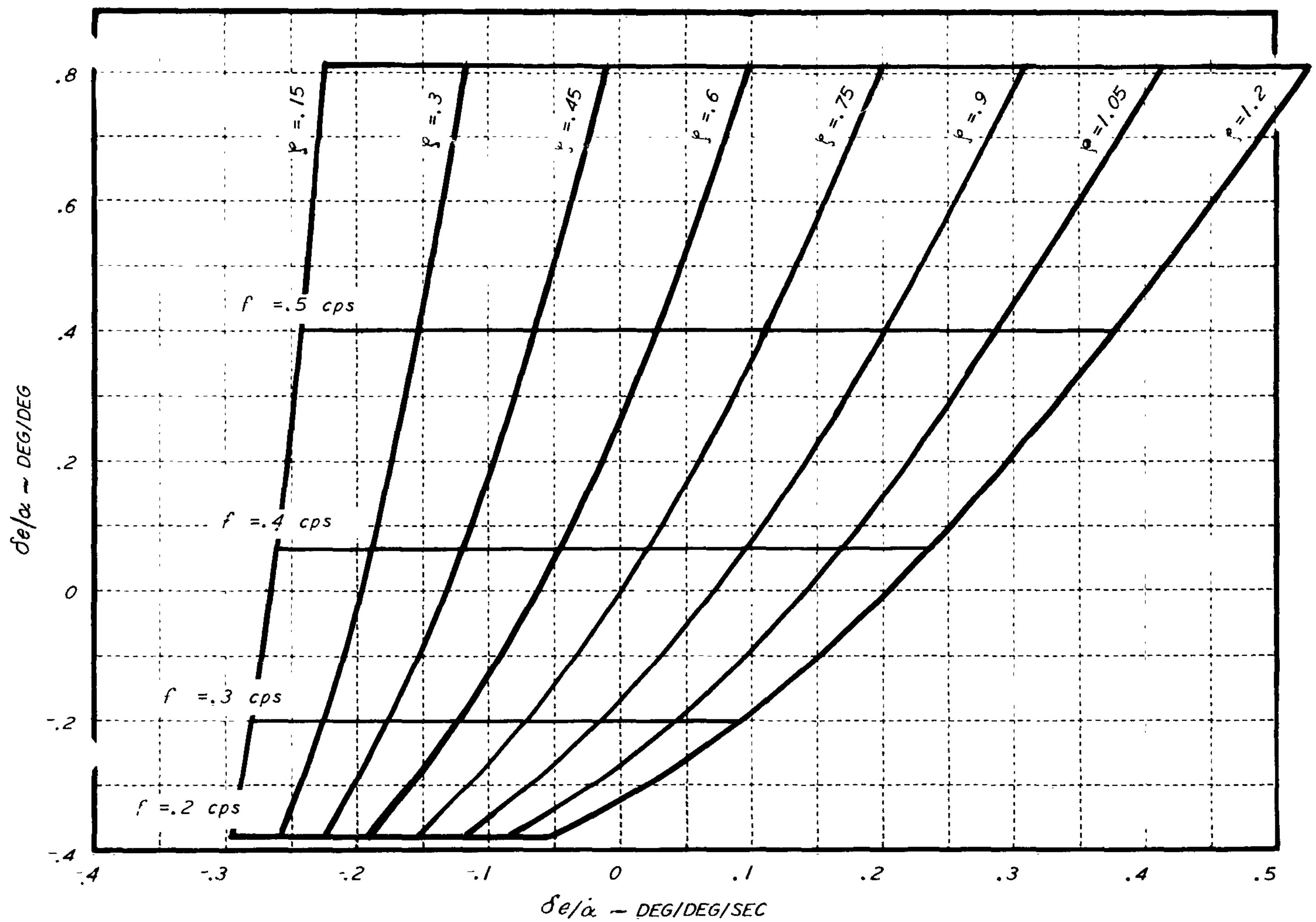

FIGURE 6 CALCULATED B-26 SHORT PERIOD CALIBRATIONS WITH NO LAGS

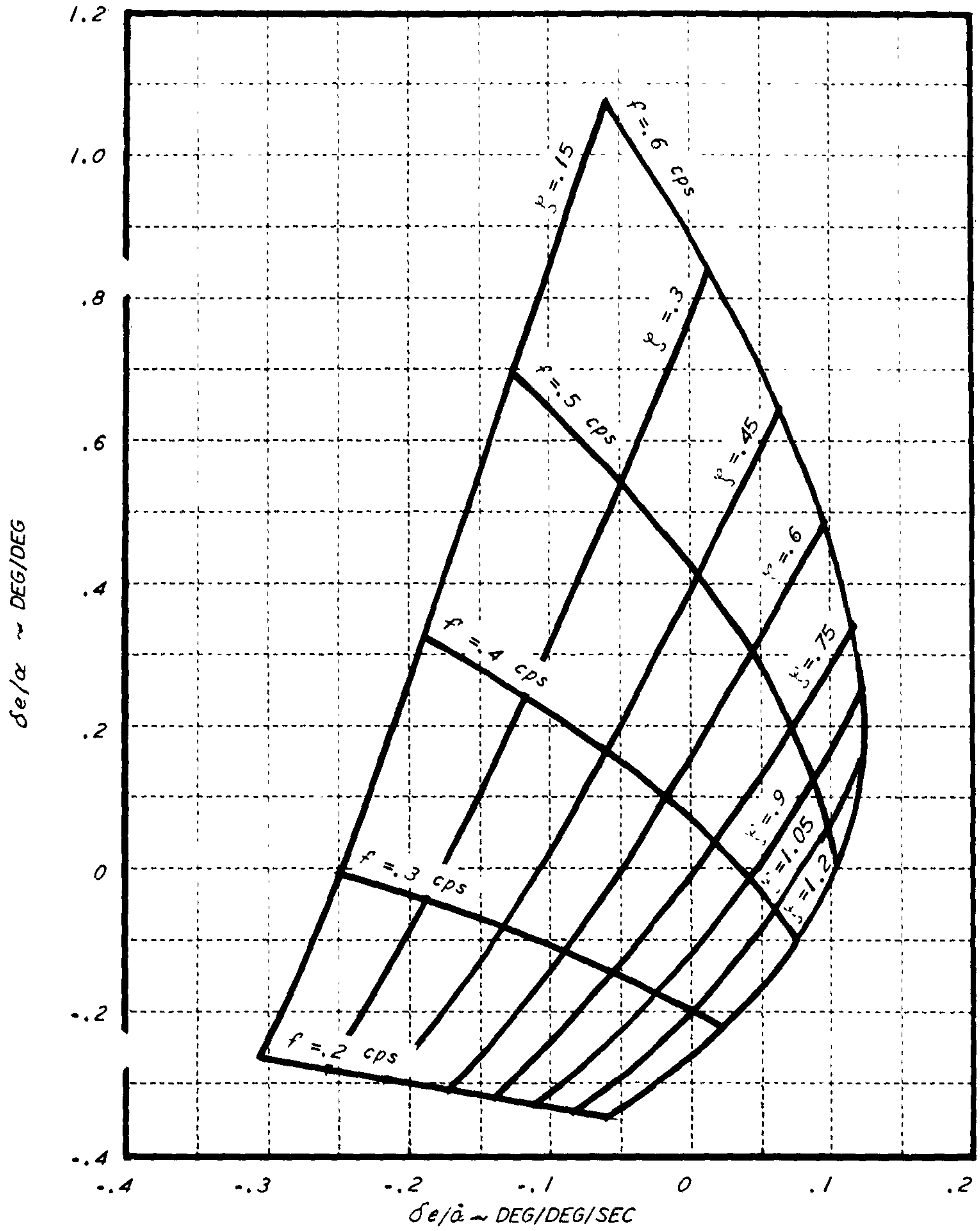

FIGURE 7 CALCULATED B-26 SHORT PERIOD CALIBRATIONS WITH LAGS

THEORETICAL CALCULATIONS INCLUDING LAGS BY LEAST-SQUARES FIT OF FLIGHT MEASUREMENTS

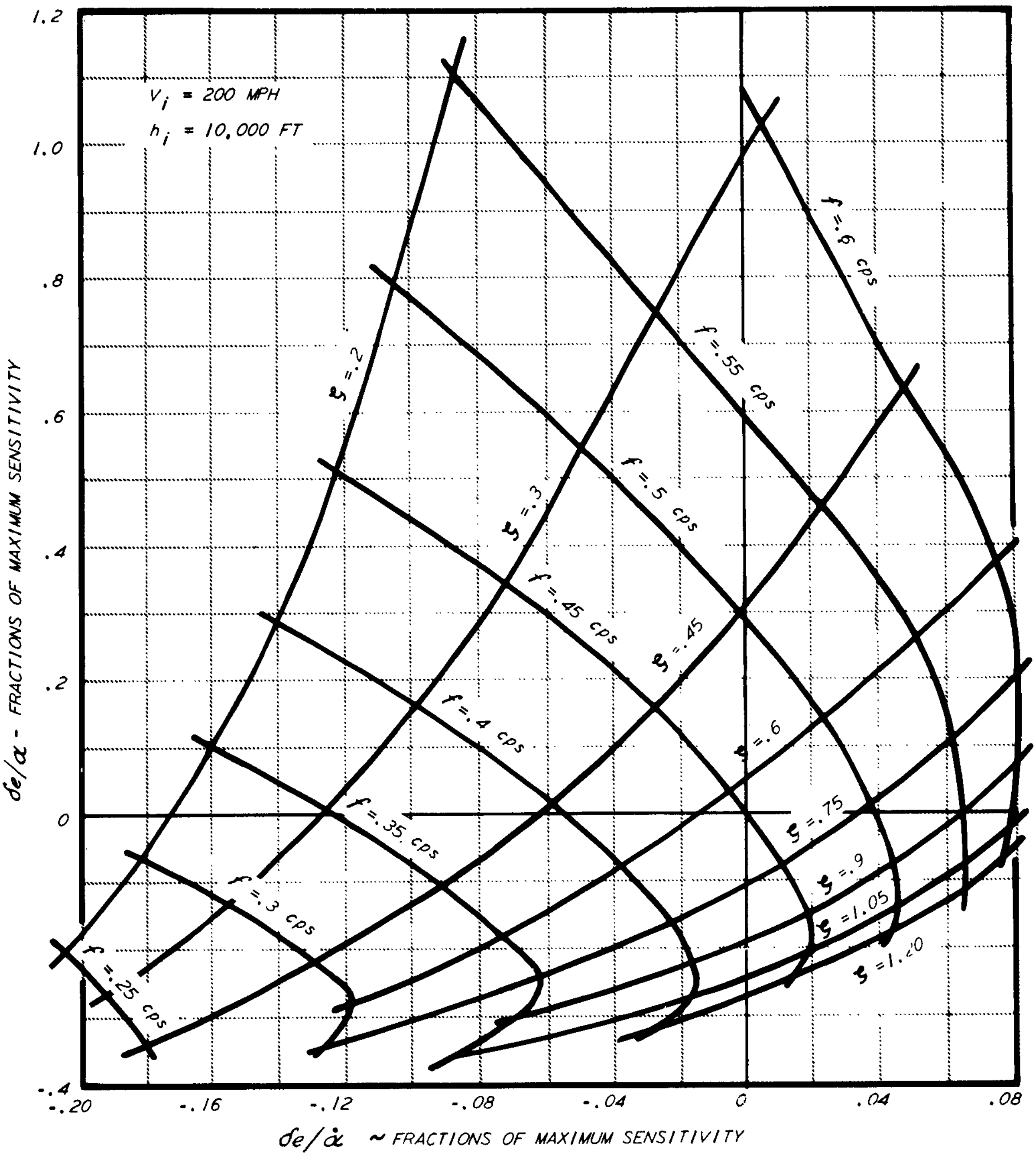

FIGURE 8 B-26 SHORT PERIOD CALIBRATION CURVE

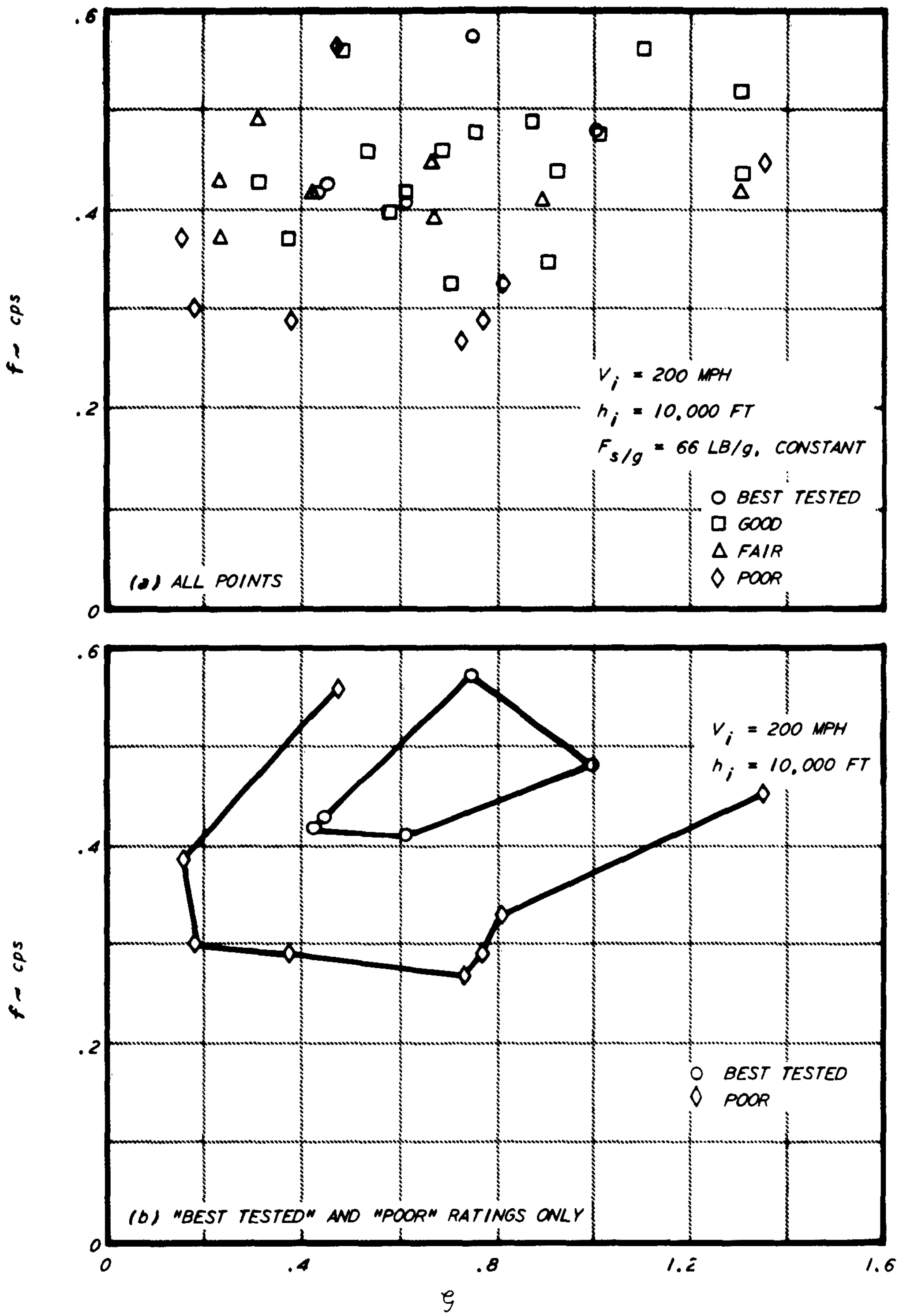

FIGURE 9 PILOT RATINGS OF INDIVIDUAL SHORT PERIOD CONFIGURATIONS

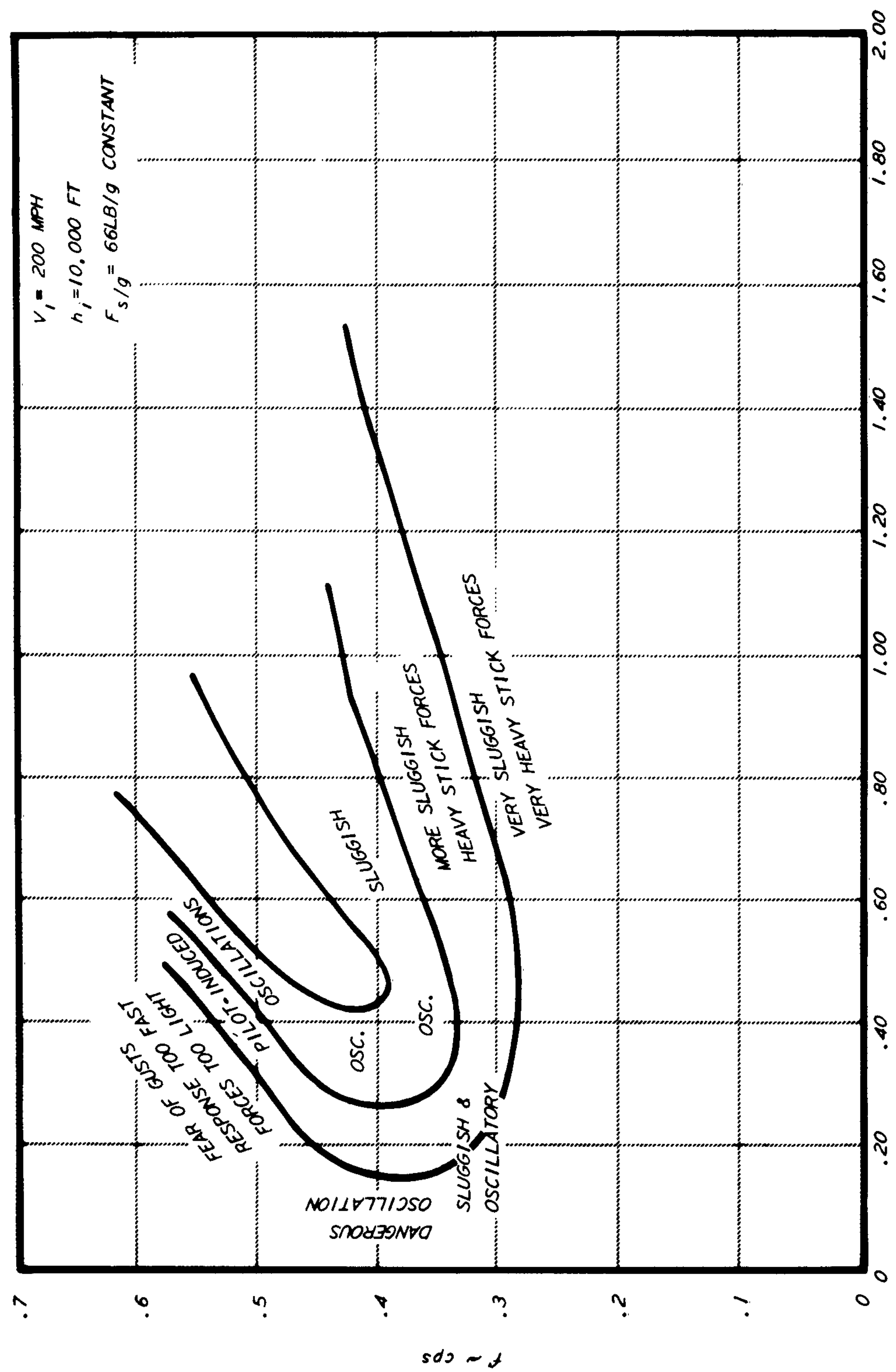

FIGURE 10 PREVALENT PILOT COMMENTS ON VARIOUS SHORT PERIOD CHARACTERISTICS IN A B-26

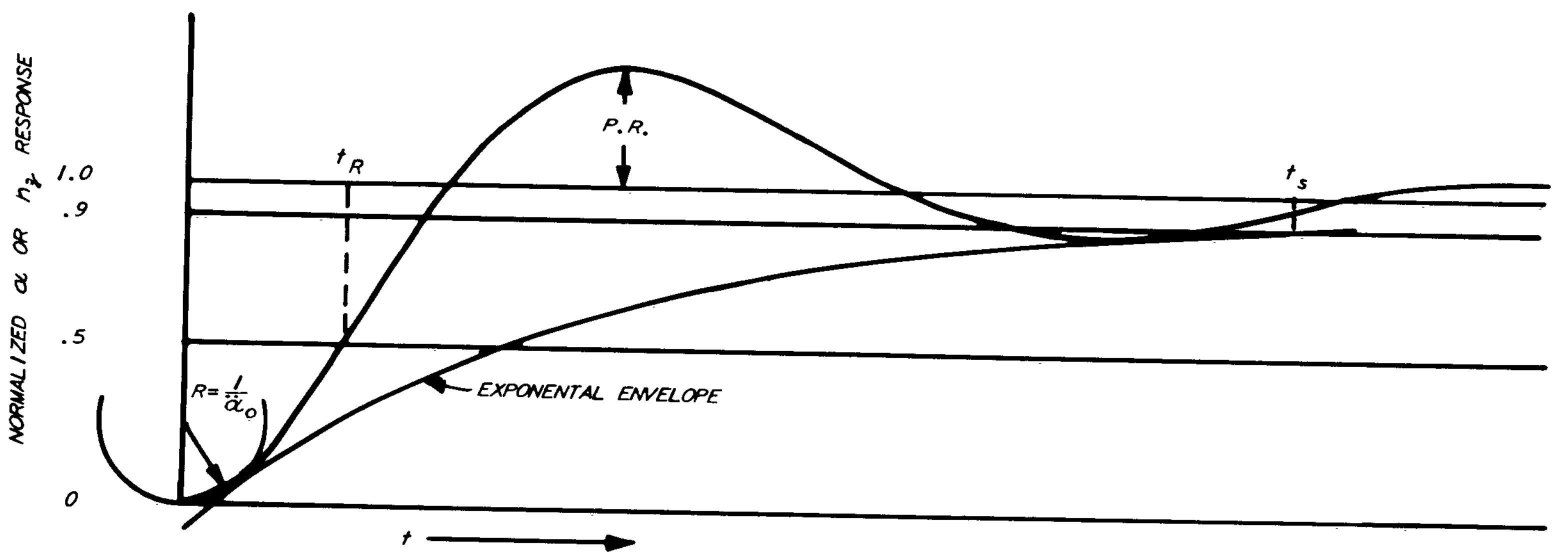

FIGURE 11 TYPICAL RESPONSE TO AN ELEVATOR STEP SHOWING INITIAL ACCELERATION, RISE TIME, PEAK RATIO, AND SETTLING TIME

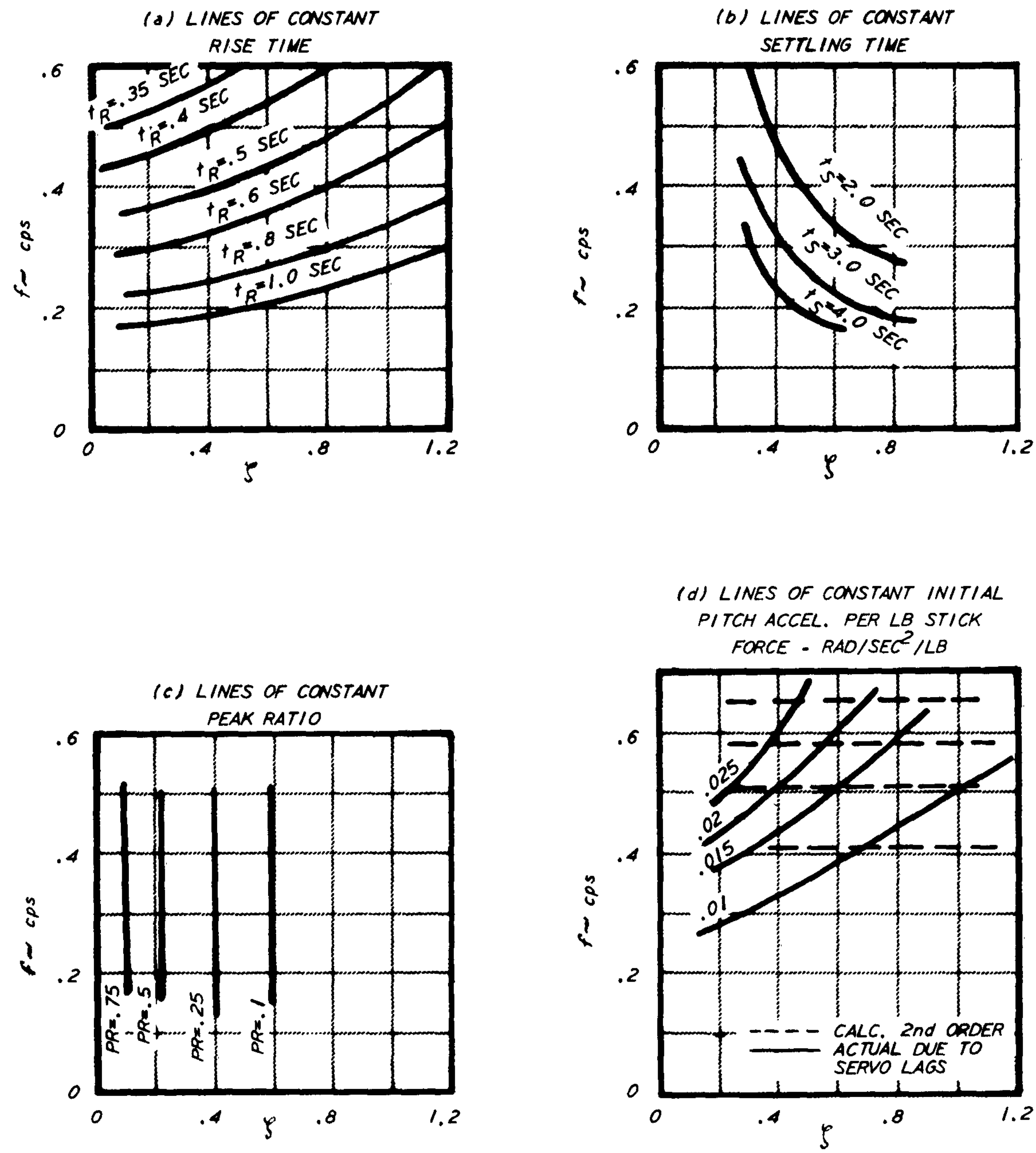

FIGURE 12 LINES OF CONSTANT RISE TIME, SETTLING TIME, PEAK RATIO, AND INITIAL PITCH ACCELERATION vs FREQUENCY AND DAMPING RATIO

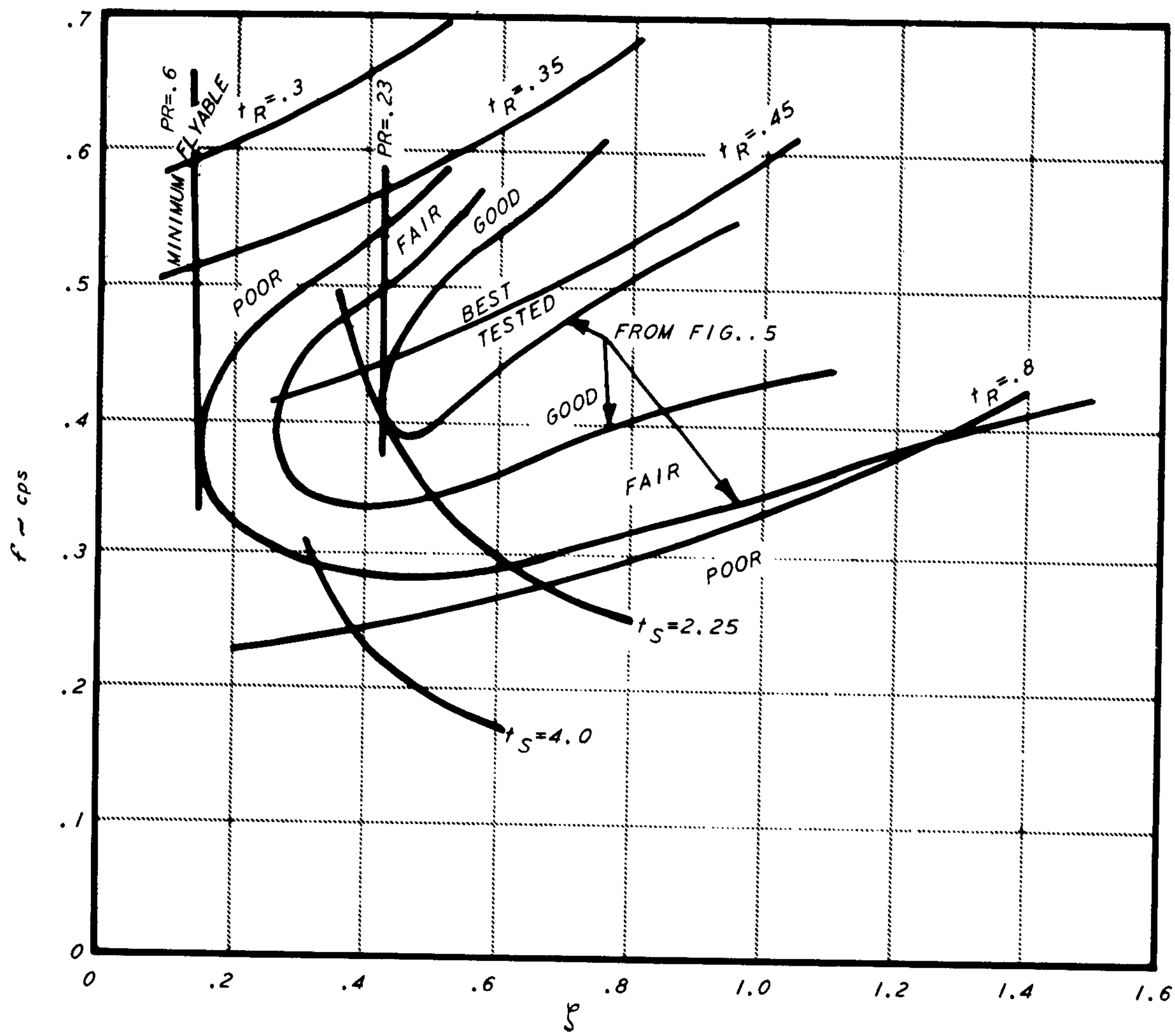

FIGURE 13 CALCULATED CURVES OF CONSTANT RISE TIME, PEAK RATIO, AND SETTLING TIME SUPERIMPOSED ON EXPERIMENTAL SHORT PERIOD BOUNDARIES OF VARYING PILOT ACCEPTANCE

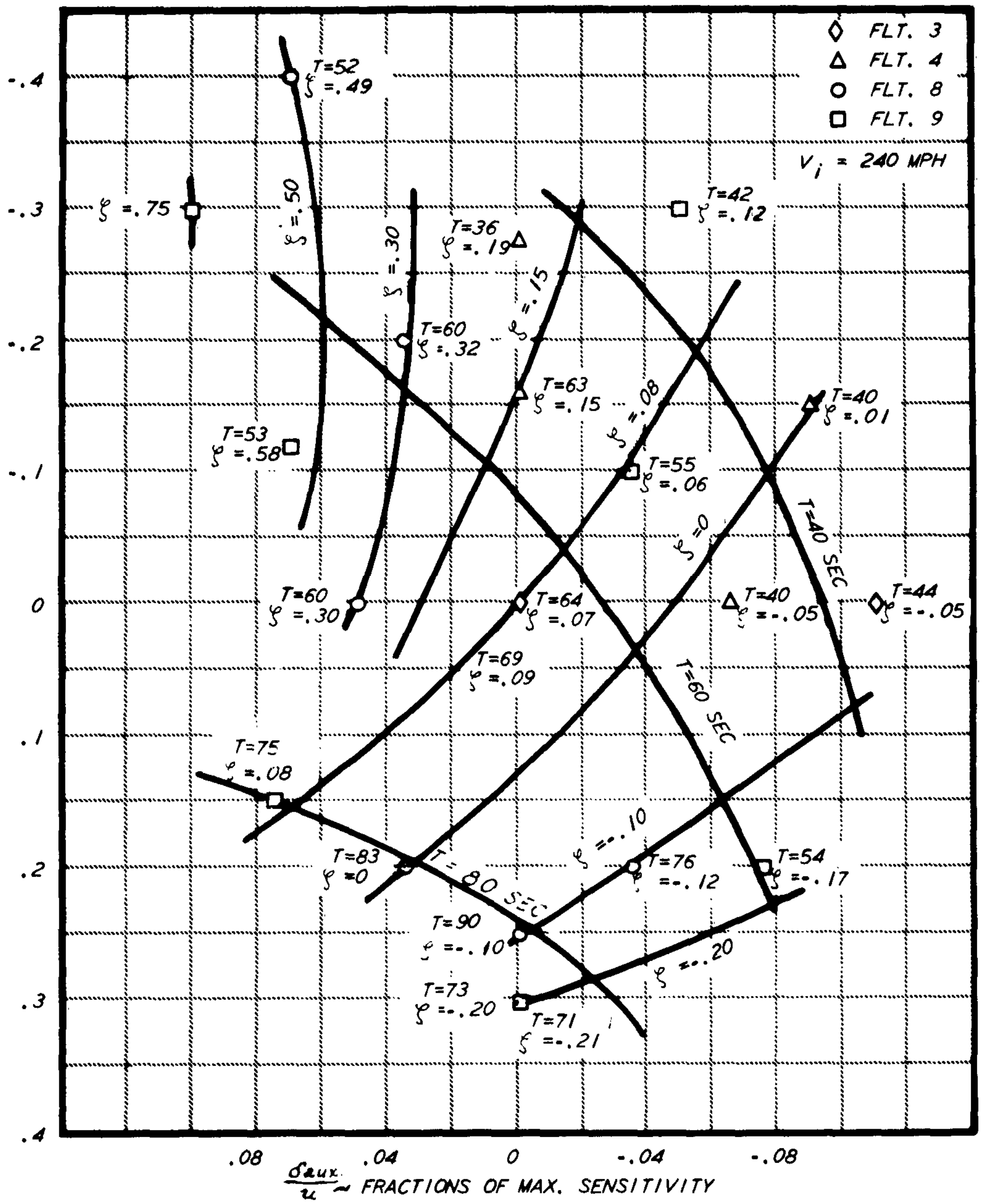

FIGURE 14 FLIGHT MEASUREMENTS OF B-26 PHUGOID DAMPING AND PERIOD vs $\frac{\delta aux}{u}$ AND $\frac{\delta aux}{\dot{u}}$ SENSITIVITIES

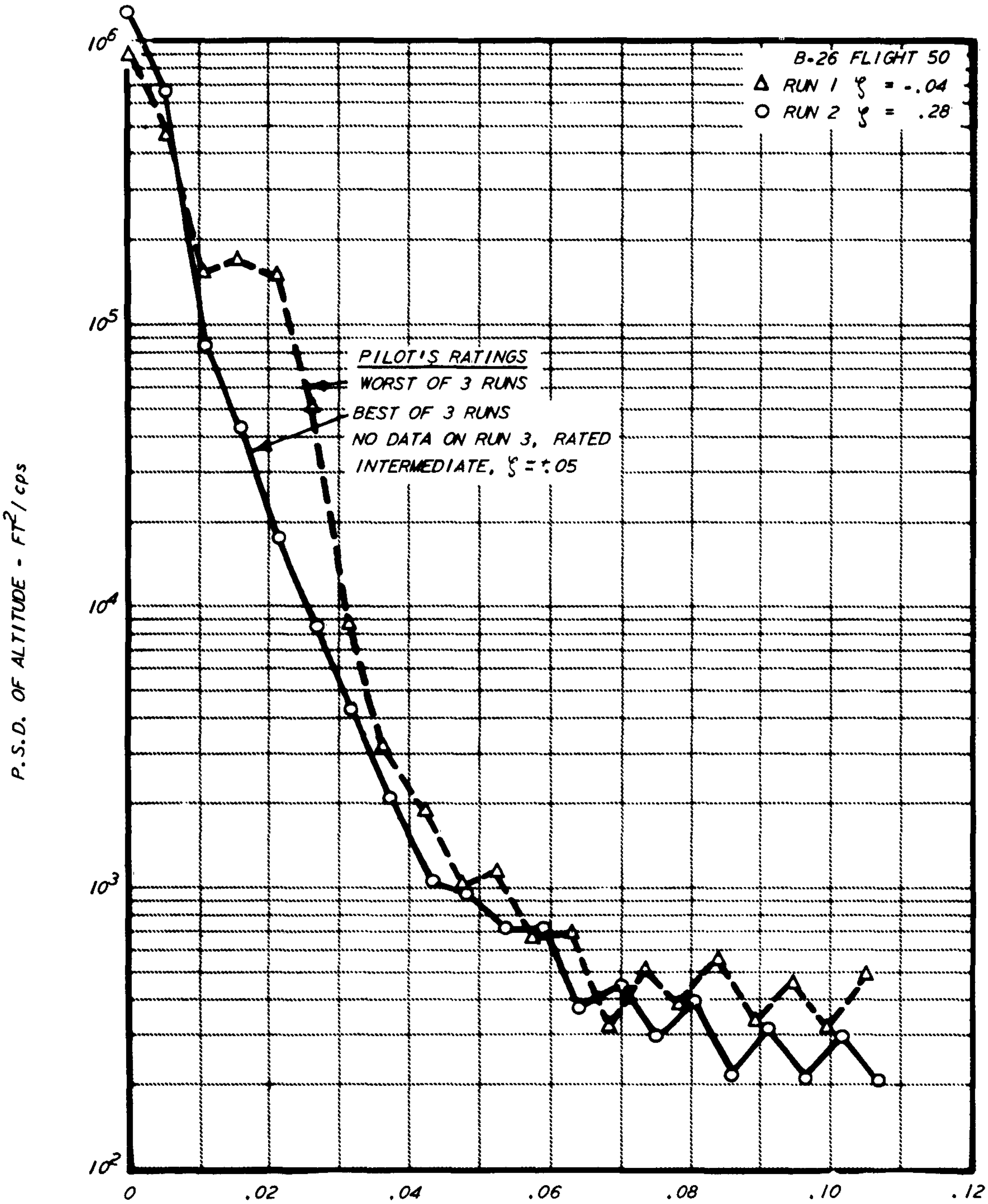

FIGURE 15 POWER SPECTRAL DENSITIES OF ALTITUDE VARIATIONS, B-26 FLIGHT 50

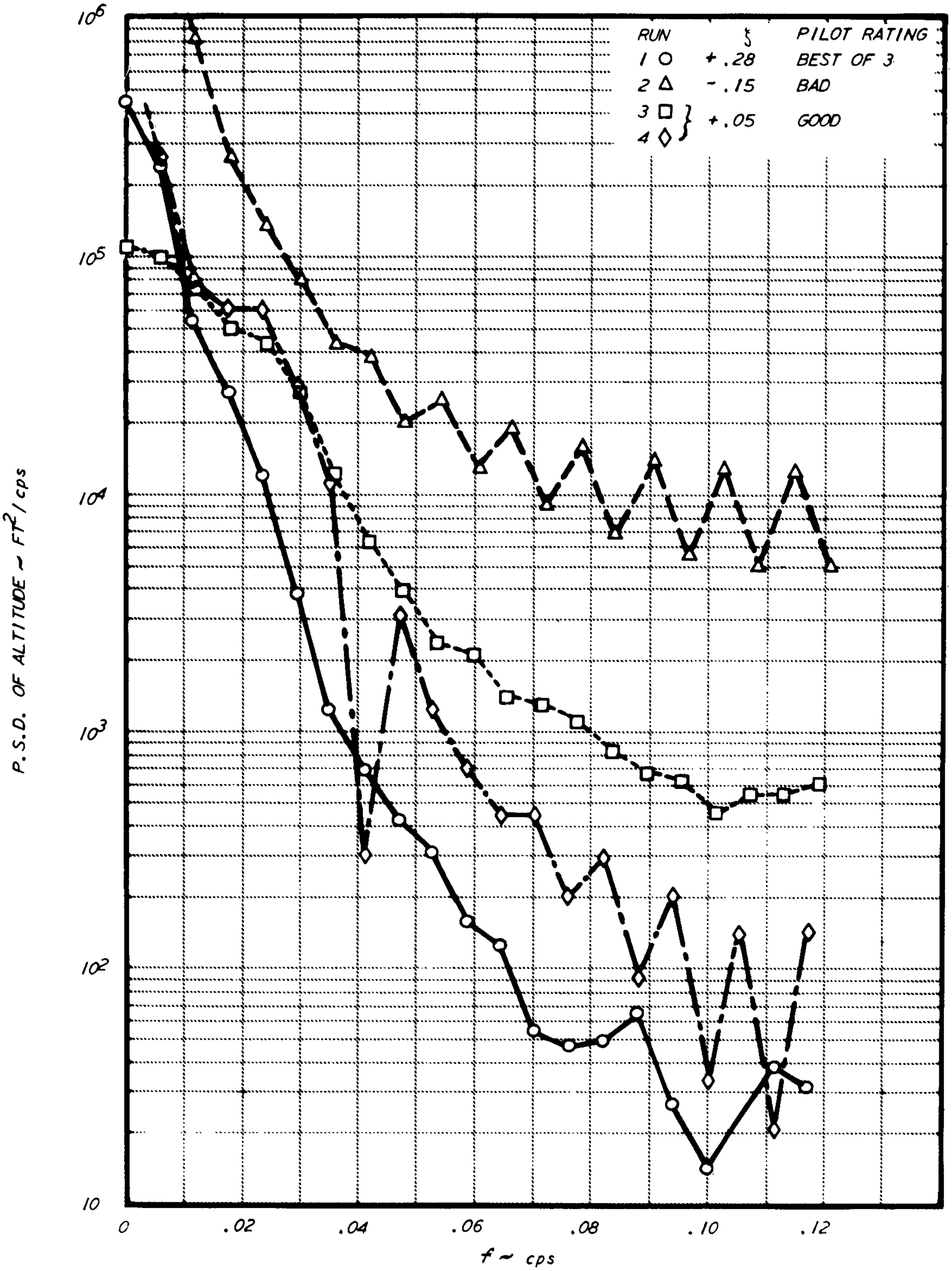

FIGURE 16 POWER SPECTRAL DENSITIES OF ALTITUDE VARIATIONS, B-26 FLIGHT 74

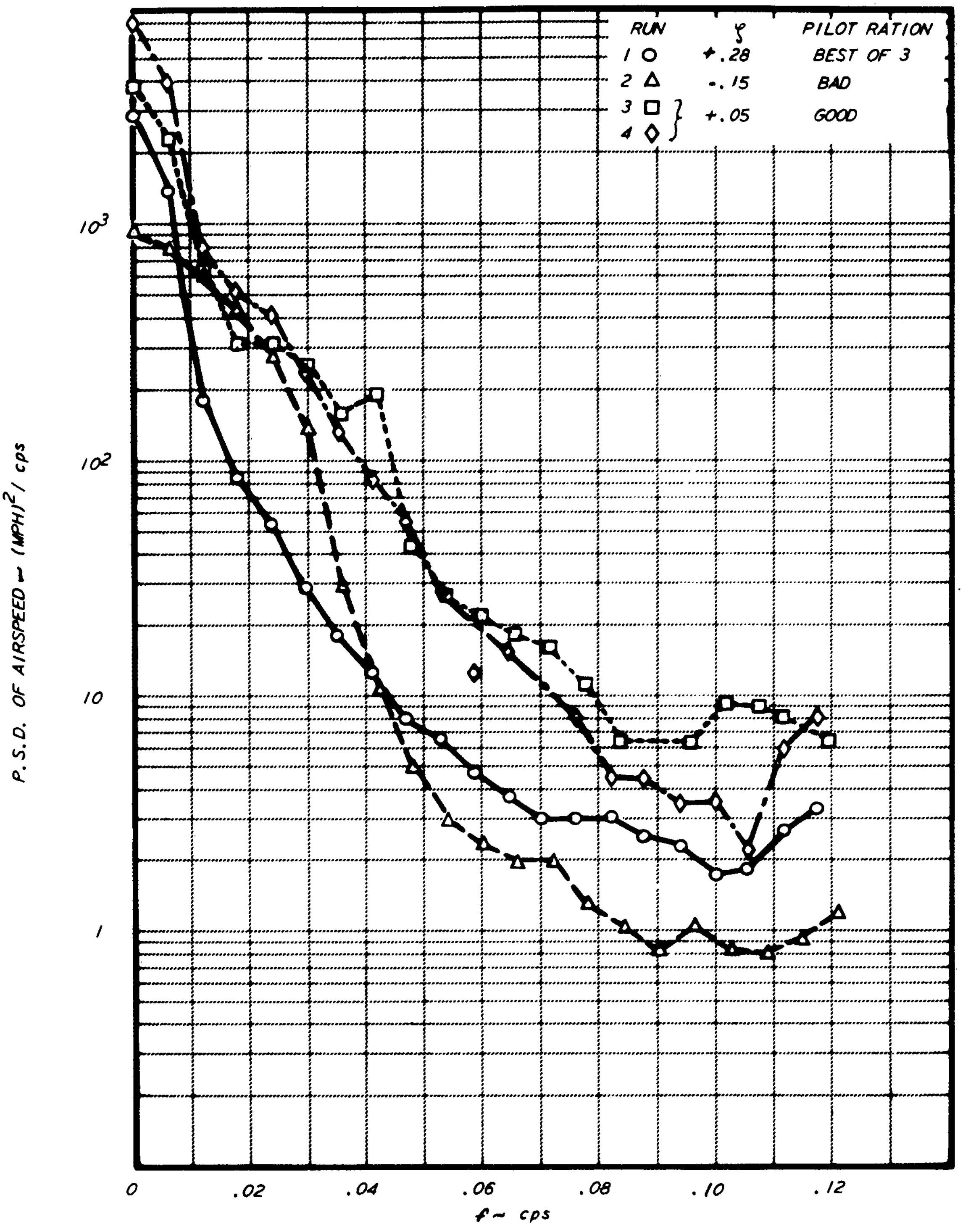

FIGURE 17 POWER SPECTRAL DENSITIES OF AIRSPEED VARIATIONS, B-26 FLIGHT 74

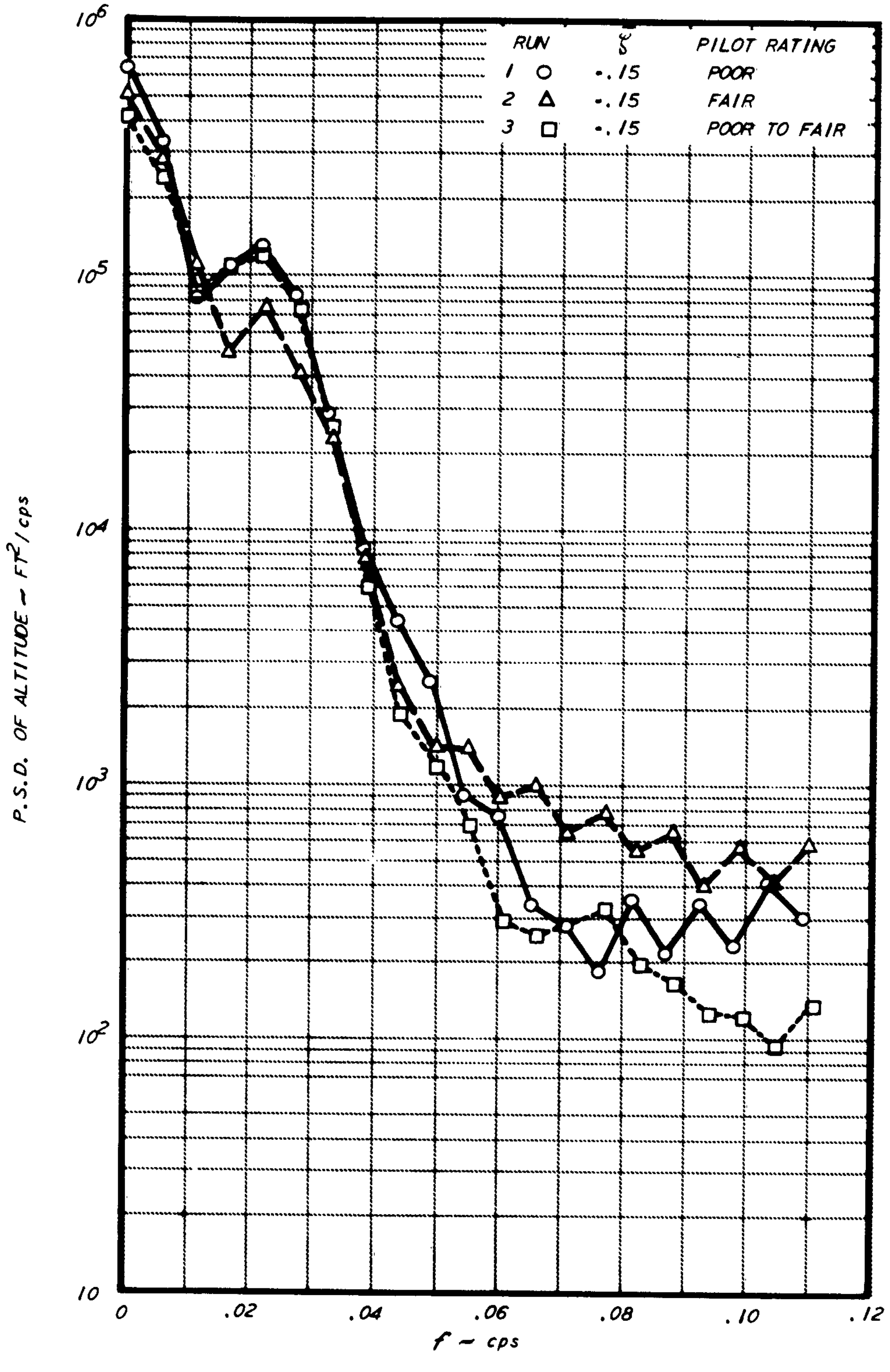

FIGURE 18 POWER SPECTRAL DENSITIES OF ALTITUDE VARIATIONS, B-26 FLIGHT 78

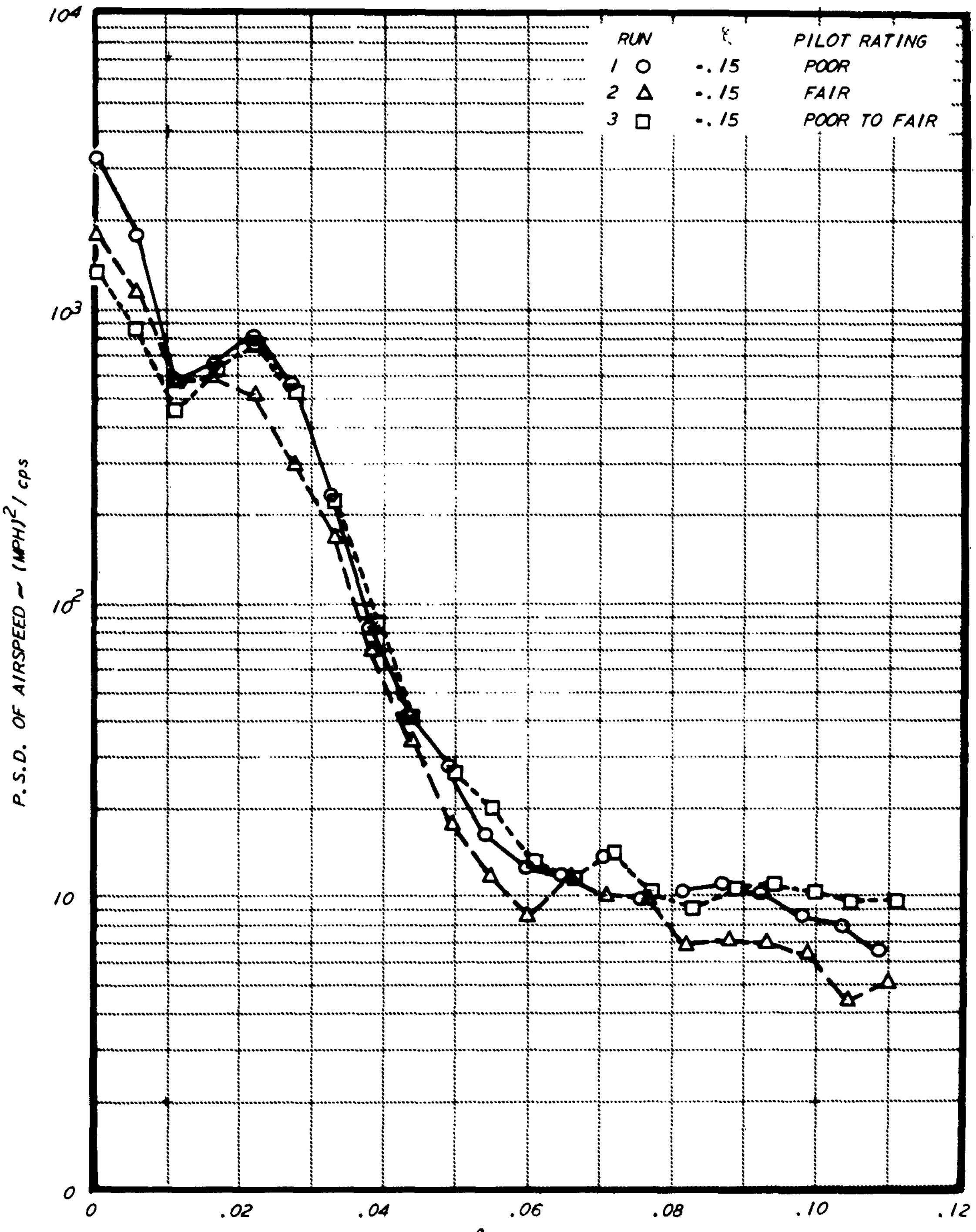

FIGURE 19 POWER SPECTRAL DENSITIES OF AIRSPEED VARIATIONS, B-26 FLIGHT 78

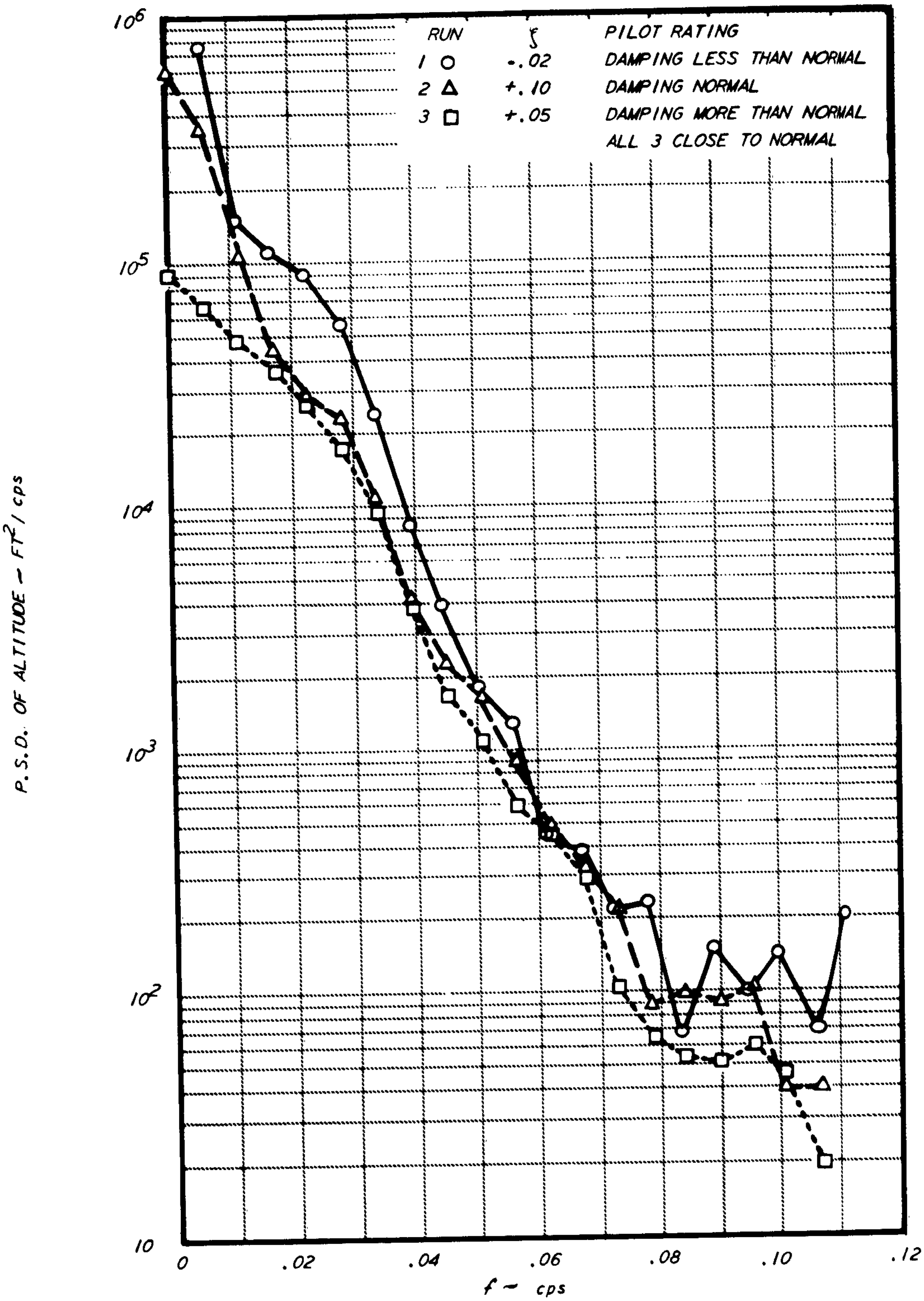

FIGURE 20 POWER SPECTRAL DENSITIES OF ALTITUDE VARIATIONS, B-26 FLIGHT 80

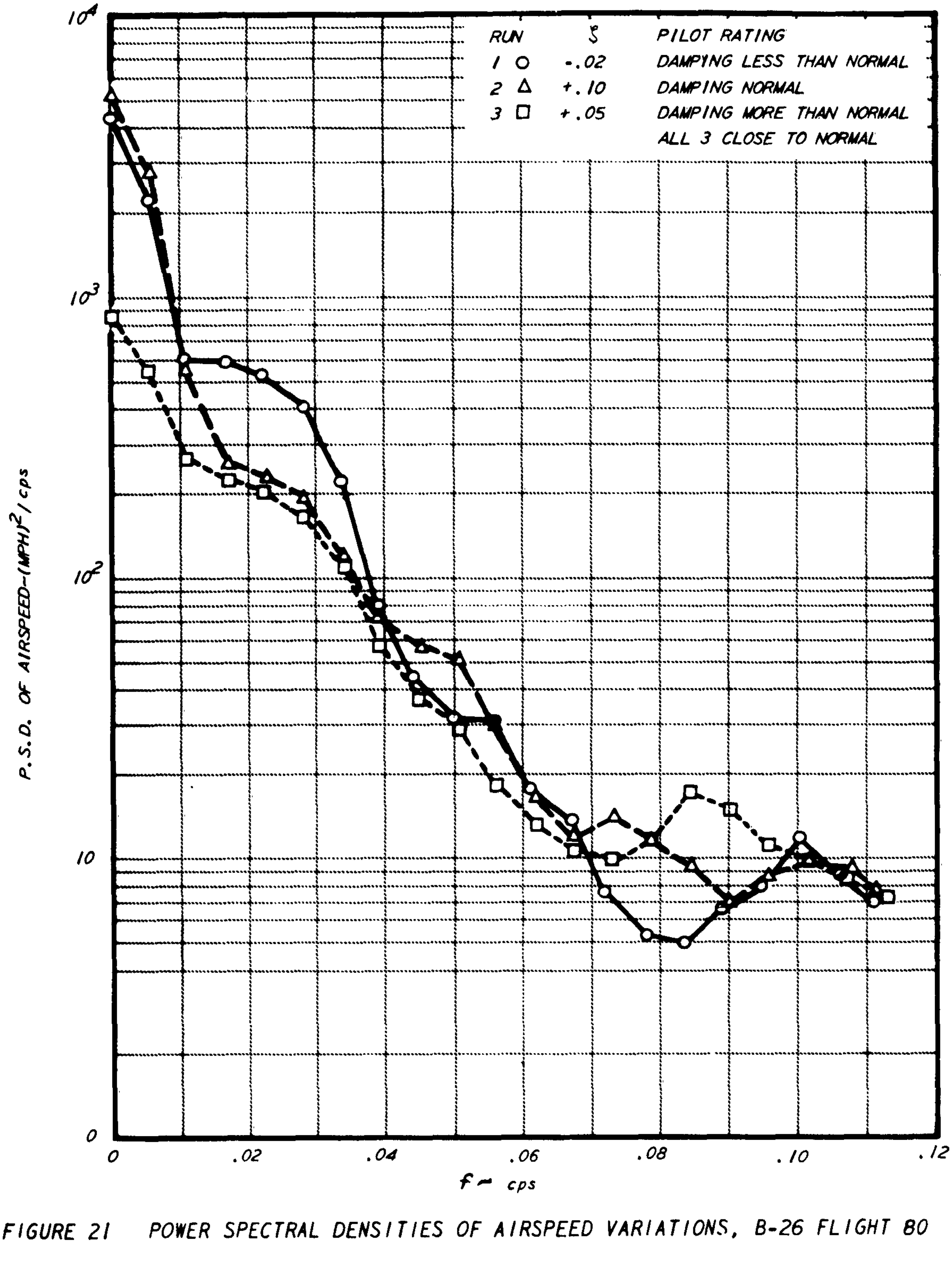

FIGURE 21 POWER SPECTRAL DENSITIES OF AIRSPEED VARIATIONS, B-26 FLIGHT 80

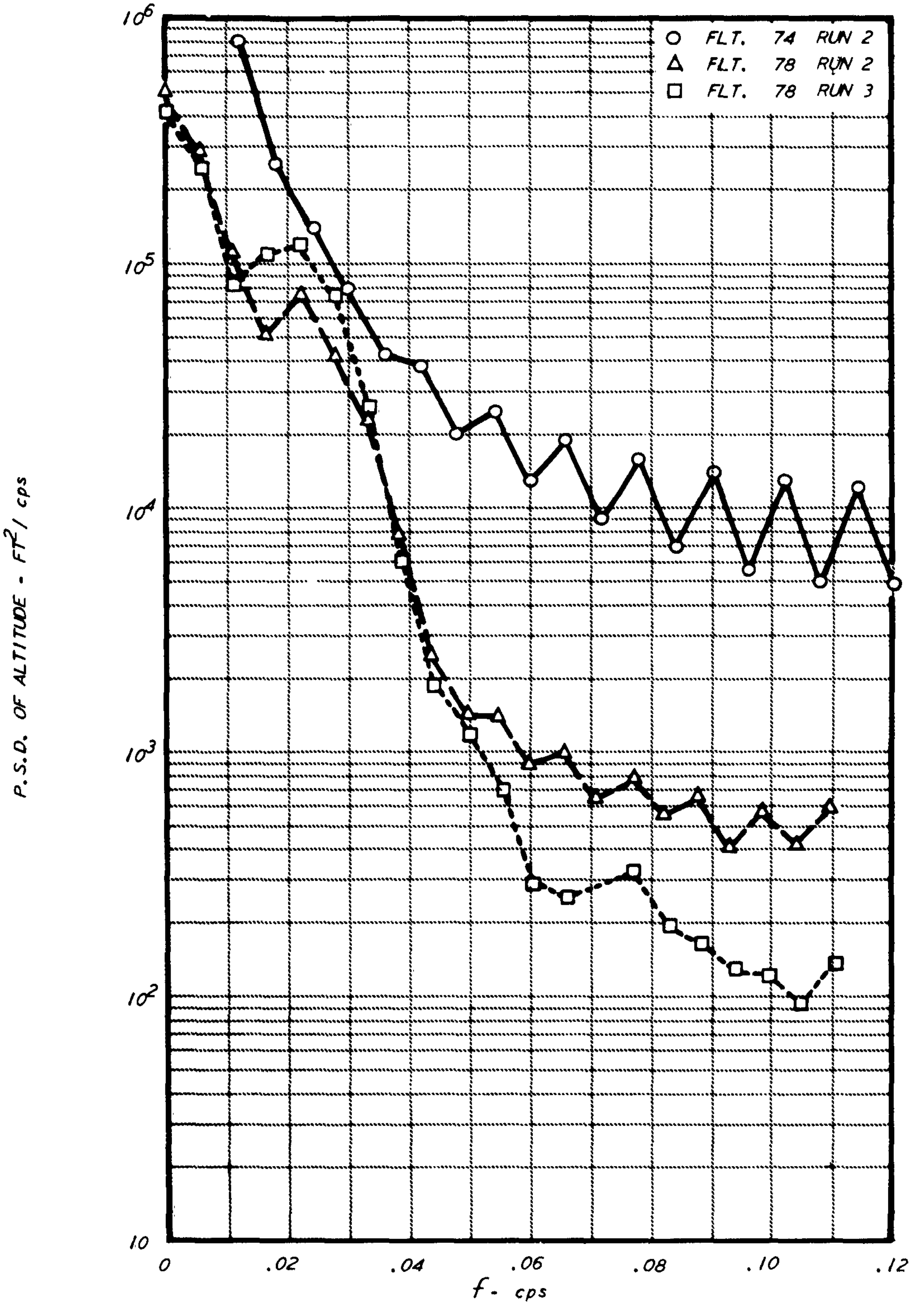

FIGURE 22 POWER SPECTRAL DENSITIES OF ALTITUDE VARIATIONS, ζ = -.15

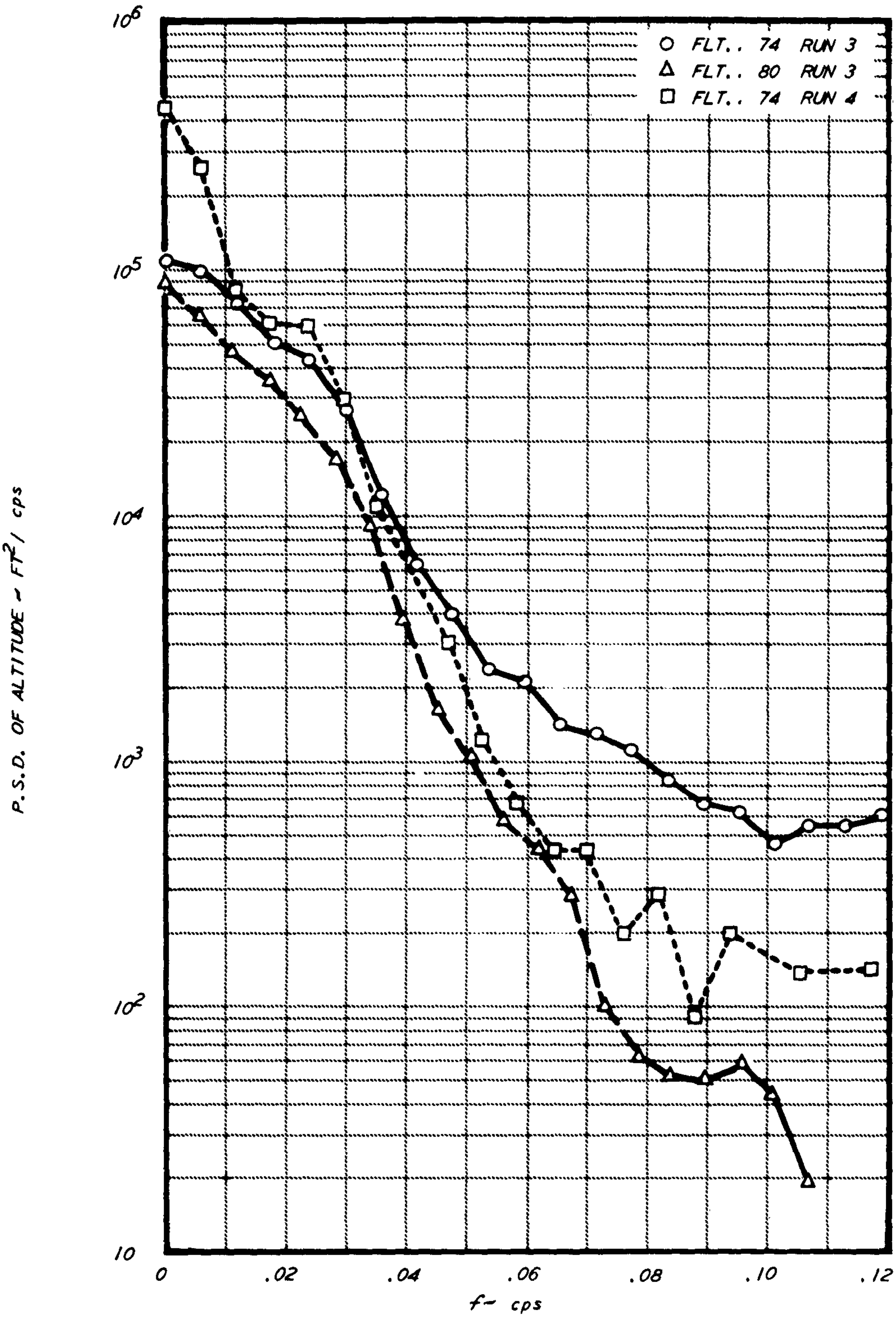

FIGURE 23 POWER SPECTRAL DENSITIES OF ALTITUDE VARIATIONS, ζ =+.05

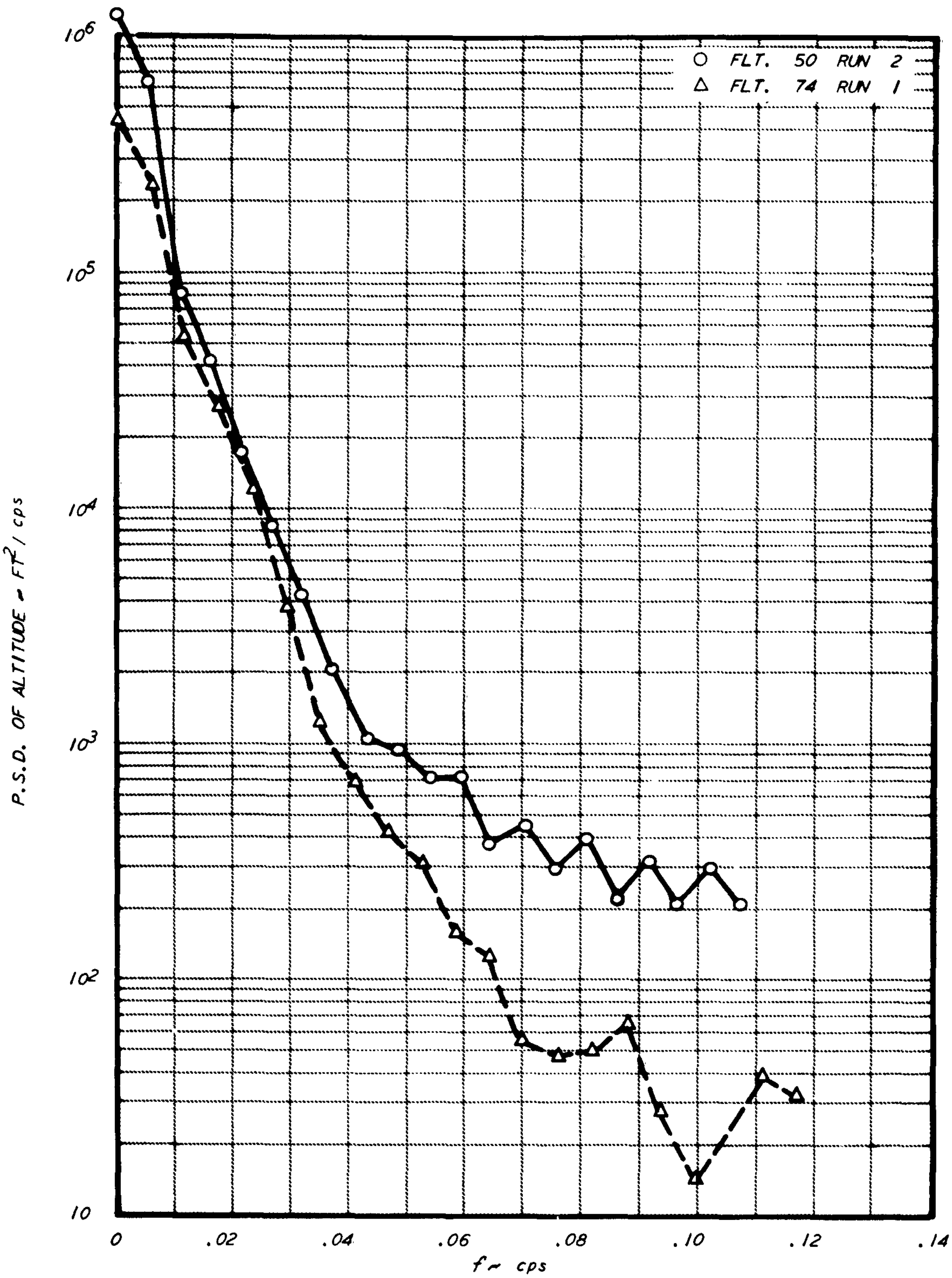

FIGURE 24 POWER SPECTRAL DENSITIES OF ALTITUDE VARIATIONS, $\zeta = +.28$

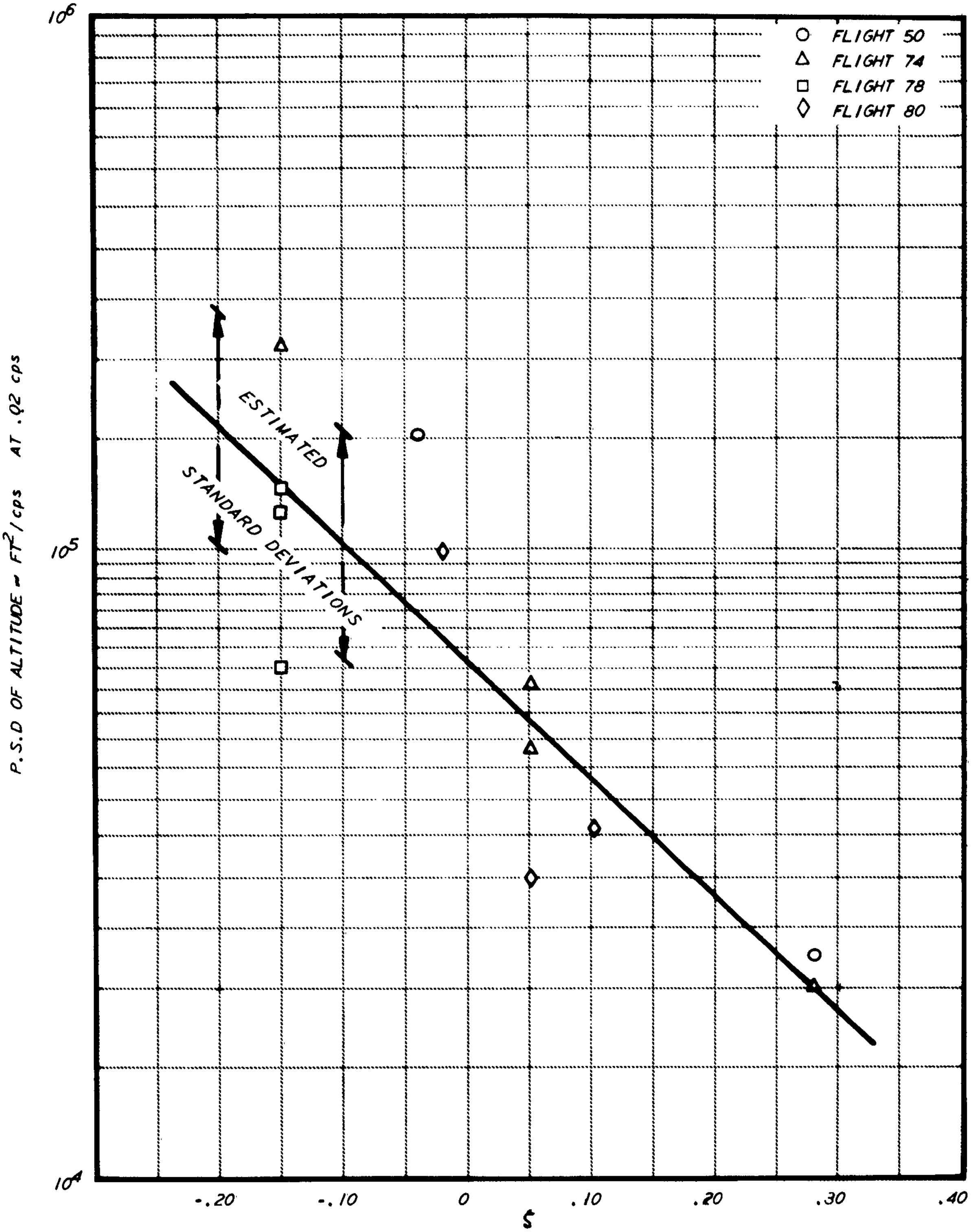

FIGURE 25 POWER SPECTRAL DENSITIES OF ALTITUDE VARIATIONS AT PHUGOID FREQUENCY vs PHUGOID DAMPING RATIO